Faculdade de Engenharia da Universidade do Porto

A Decision Support System for Investments in Public Transport Infrastructure

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This thesis is dedicated to Sofia, Gabriel and Rodrigo.

ABSTRACT

When public authorities face the need to improve a transportation system, they normally have to make a difficult choice among a set of technological and operational alternatives. To help the correct evaluation of each alternative and its impacts, costs and benefits, it would be useful to have a decision support system (DSS) based on approaches such as Multi-Criteria Decision Analysis (MCDA) and/or Cost Benefit Analysis (CBA).

Among the many impacts caused by a public transportation system, typically those on the land use are not adequately considered in the decision-making processes, mainly because they are hard to monetize, they are often considered as value transfer instead of value creation, and they are too complex to be assessed by traditional transport modeling tools. To overcome these weaknesses, the objectives of this research are to identify and measure the impacts of transit systems on land use and accessibility, and to consider those impacts in decision-making processes, along with more traditional financial and transport related impacts. For this purpose, a DSS, combining a land use and transport model with a MCDA model, was developed. This system was assessed in a small case study, where Bus Rapid Transit (BRT) and Light Rail Transit (LRT) projects are presented, and in a real case study, the *Green Line extension* project in Boston, the USA.

The DSS incorporates a range of criteria and subcriteria organized in a hierarchical manner, covering a variety of decision aspects, expert opinions and sensitivity and risk analysis. It aims to more accurately, and realistically reflect uncertainties and exogenous conditions that may significantly affect the costs and the benefits of a project. Consequently, it facilitates public debate about investment alternatives, since it makes it possible to present, in a structured way, the decision problem to the affected community and decision-makers.

Keywords: BRT; LRT; Multi-Criteria Decision Analysis; Land Use and Transport; Investment analysis

RESUMO

Quando as autoridades públicas enfrentam a necessidade de melhorar um sistema de transporte, têm normalmente de fazer uma escolha difícil entre um conjunto de alternativas tecnológicas e operacionais. Para ajudar a avaliação correta de cada alternativa e seus impactos, custos e benefícios, seria útil contar com um sistema de apoio à decisão (DSS) baseado em abordagens tais como Análise Multicritério (MCDA) e / ou Análise de Custo Benefício (CBA).

Entre os muitos impactos causados por um sistema de transporte público, tipicamente aqueles no uso do solo não são adequadamente considerados nos processos de tomada de decisão, principalmente porque são difíceis de monetizar, são geralmente considerados como transferência de valor em vez de criação de valor, e são muito complexos para serem avaliados por ferramentas de modelação de transporte tradicionais. Para superar essas fraquezas, os objetivos desta pesquisa são identificar e medir os impactos dos sistemas de transporte público sobre o uso do solo e a acessibilidade, e considerar esses impactos nos processos de tomada de decisão, juntamente com os impactos financeiros e de transportes mais tradicionais. Para isso, foi desenvolvido um DSS, combinando um modelo de uso do solo e transporte com um modelo MCDA. O DSS foi então aplicado em um pequeno estudo de caso ilustrativo, onde projetos de sistemas Bus Rapid Transit (BRT) e Light Rail Transit (LRT) são apresentados, e depois em um estudo de caso real, o projeto *Green Line Extension* em Boston, EUA.

O DSS incorpora uma série de critérios e subcritérios organizados de forma hierárquica, abrangendo uma variedade de aspectos de decisão, opiniões de especialistas e análises de risco e sensibilidade, de forma precisa e realista, refletindo incertezas e condições exógenas que podem afetar significativamente os custos e os benefícios de um projeto. Consequentemente, facilita o debate público sobre alternativas de investimento, uma vez que permite, de forma estruturada, apresentar o problema de decisão à comunidade afetada e aos decisores.

Keywords: BRT; LRT; Análise Multicritério; Uso do solo e transportes; Análise de investimentos

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LIST OF ABBREVIATIONS

€	Euro
A1	Alternative 1
AHP	Analytic Hierarchy Process
APAX	Auto Passenger
AVL	Automatic Vehicle Location
BA	Baseline Alternative
BCR	Benefit Cost Ratio
BHLS	Bus with High Level of Service
BMA	Boston Metropolitan Area
BRT	Bus Rapid Transit
CBA	Cost Benefit Analysis
CBD	Central Business District
CO_2	Carbon Dioxide
CR	Consistency Ratio
CTPS	Central Transportation Planning Staff
DAT	Drive to access transit
DI	Diversity Index
DSI	Dissimilarity Index
DSS	Decision Support System
DU	Dwelling Units
EI	Entropy Index
EJ	Environmental Justice
FAR	Floor Area Ratio
FTA	Federal Transit Administration
GLX	Green Line Extension Project

GWR	Geographic Weighted Regression
HHI	Herfindahl-Hirschman Index
HR	Heavy Rail Transit
HRT	Heavy Rail Transit
In	Inbound Boston
IRR	Internal Rate of Return
ITS	Intelligent Transportation Systems
k	One Thousand
km	Kilometer
KM	Kilometer
LRT	Light Rail Transit
LUT	Land Use and Transport
M	One Million
Mass DOT	Massachusetts Department of Transportation
Max.	Maximum
MBTA	Massachusetts Bay Transportation Authority
MCDA	Multi-Criteria Decision Analysis
min.	Minutes
Min.	Minimum
MIT	Massachusetts Institute of Technology
MIT-FSM	MIT Boston Metro Region Four Step Model
MPO	Boston Region Metropolitan Planning Organization
NB	No Build
Non-EJ	Non-environmental Justice
NPV	Net Present Value
O&M	Operating and Maintenance Costs

O/D	Origin/Destination
Out	Outbound Boston
PAC	Growth Acceleration Program
PAX	Passenger
POP	Population
pphpd	Passenger per hour per direction
ROW	Right-of-Way
SCBA	Social Cost Benefit Analysis
SOV	Single Occupancy Vehicle
TAZ	Traffic Analysis Zone
TM	TransMilenio
TOD	Transit Oriented Development
US$	American Dollar
VOSL	Value of Statistical Life
VTTS	Value of Travel Time Savings
WALK	Walk
WAT	Walk to access transit

1. INTRODUCTION

- Motivation
- Objectives
- Research questions
- Research methodology

1.1. Motivation

As cities grow, so does the need for better public transportation systems. With limited budgets and under an environmentally-constrained setting, it is paramount that transportation systems and land use are considered together, thus ensuring higher sustainability levels. However, changes in land use induced by new transportation services or infrastructure, typically occurring within half-mile from stations, are not adequately considered in decision-making[1], mainly because they are hard to monetize to fit in a traditional Cost Benefit Analysis (CBA) (Börjesson et al., 2014; Damart and Roy, 2009; Douglas et al., 2013; Eliasson, 2013; May et al., 2008). Normally, these benefits are often considered as value transfer instead of value creation, and they are too complex to be assessed by traditional transport modeling software. Gains in accessibility, density, mixed-use and property values are some impacts of transportation services that reflect changes in land use and should be considered when designing or re-designing those services.

Recent research clearly shows that proximity to transportation stations can increase local accessibility and therefore influence the value of surrounding properties and rents, affect population and job density, attract business and services and spur economic development. The magnitude of these impacts can greatly vary according to systems, urban patterns and local market behaviors. It is frequently considered (Vuchic, 2002) that rail systems, e.g. Light Rail Transit (LRT), have more impact on land use, when compared to road systems, mainly because of the "sense of permanence" they bring. Currie (2006) and Deng and Nelson (2011) state differently, arguing that road systems such as Bus Rapid Transit (BRT) can have substantial positive impacts on land use, mainly when integrated land use transport plans are applied. Table 1 lists some cases showing the impact of transit on land use[2].

There are several approaches for understanding and handling land use changes in terms of decision-making processes for transportation systems. These approaches are used in more theoretical research, in academia (Banai, 2010; Bertolini et al., 2005; da Silva et al., 2008; Hull et

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[1] In this thesis, the term decision-making refers to major capital investments on public transport infrastructure, i.e. the process for choosing an investment alternative to build, among a set of alternatives.

[2] For similar studies regarding the impacts of transit on land use see Banister and Thurstain-Goodwin (2011); Knowles and Ferbrache (2016); Debrezion et al. (2007), (2011); Deng and Nelson (2011); Hensher et al. (2012); Legaspi et al. (2015); Stokenberga (2014); Wirasinghe et al. (2013).

al., 2012; Thomopoulos and Grant-Muller, 2013) and in practice by government funding agencies (FTA, 2015; MacKie and Worsley, 2013). These approaches can be summarized as follows:

- political/planning approaches: value capture mechanisms, Transit Oriented Development (TOD) plans;
- methodological/modeling approaches: Land Use and Transport (LUT) models, evaluation at face values.

Table 1 - Impacts of transit on land use

City	Mode	Impact	Reference
Bogotá	BRT	Residential prices up between 5.8% and 17%	Perdomo Calvo et al., 2010
Pittsburgh	BRT	A residential property 300 meters away from a station is valued approximately US$ 10,000 less than a property 30 meters away from it	Perk and Catalá, 2009
Seoul	BRT	54% increase in employment density	Kang, 2010
Buffalo	LRT	Residential prices up between 2% and 5%	Hess and Almeida, 2007
Freiburg	LRT	Office rents per square meter on the periphery were nearly 37% lower than at similar locations served by the system	Hass-Klau and Crampton, 2005
Nantes	LRT	About 25% of all new offices were located along a light rail line	Hass-Klau and Crampton, 2005
Mexico City	Metro	Residential density increased significantly more around stations	Guerra, 2014

Value capture mechanism takes part of the monetary gains from surrounding properties to help financing the transit system, which can then be evaluated with traditional CBA as a capital influx (Levinson and Zhao, 2012), while TOD plans ensure that zoning regulations near stations will favor dense and mixed land use patterns that, in the medium/long term, will help increase station ridership. Instead of estimating and evaluating the changes caused by transport investments on land use, a TOD plan is evaluated, for instance with Multi-Criteria Decision Analysis (MCDA) (FTA, 2015). In this way, the decision-maker knows, to a certain degree, that the changes will happen, even if their impact cannot be fully estimated. On the other hand, LUT models can estimate changes in land use triggered by transit systems, typically based on project development catalogs and hedonic models, and update baseline population and activity data, that are typically the inputs for four-step models – this process is iterated several times, and then the evaluation is performed. Other metrics (such as accessibility), evaluated at their face value, by MCDA-type methods, are less common in the literature (Hull et al., 2012).

TOD plans can be difficult to implement, because responsibilities and decision-making processes are fragmented (Börjesson et al., 2014). Value capture approaches can also be difficult to use, as they demand some articulation between different stakeholders to guarantee their application (Martínez, 2010). On the other hand, LUT models are also challenging, as they are rather sophisticated, data intensive, and expensive to build and to keep updated. Hence, a new decision system, incorporating land use changes, not requiring TOD plans, value capture mechanisms or sophisticated LUT models, may be quite valuable in practical terms.

1.2. Objectives

Taking into account the above discussion, the objectives of this research are:

1. Understand current decision-making processes focusing on, but not limiting to, BRT and LRT systems;
2. Understand the impacts of transit systems on land use and accessibility;
3. Measure these impacts; and
4. Consider those impacts in the relevant decision-making processes.

The first and second objectives aim at identifying how current decision-making is carried out, when it comes to choose a transit investment alternative, among a set of potential projects, and how transit systems, typically within half-mile from transit stations, affect land use and accessibility. To support these objectives, a structured literature review was performed.

For the third objective, as referred before, LUT models cannot in general be used, as they are rather expensive to build and to keep updated. Such difficulties might hinder a broader interest on analyzing, estimating and incorporating in decision-making processes impacts triggered by transit systems on land use and accessibility. Hence, a practical way of forecasting impacts of transit systems on land use and accessibility was developed.

Finally for the fourth objective, as stated by Meyer and Miller (2001), Quinet (2000) and TRB (2011), appraisal tools such as CBA normally do not consider land use impacts, despite the substantial benefits and costs that can emerge. Problems as complex as the implementation of transit networks need a more sophisticated decision support system (DSS) that considers the diversity of criteria related to an urban intervention with such magnitude. Usually CBA fits very well to problems for which the process of impact monetization is easy, i.e., giving a monetary value for each cost and benefit, but for problems where it is not, others appraisal tools should be used, such as MCDA.

1.3. Research questions

The following research questions resulted naturally from a comprehensive literature review and the identification of a set of relevant gaps:

- **Question 1**: Have BRT and LRT some impact on accessibility, land use, density and land value that can be measured?
    - **1.1**: Are those impacts mostly benefits rather than costs?
    - **1.2**: Can those benefits and costs help decision-making?
    - **1.3**: Can those benefits (mainly density increase and land use mix increase) induce medium and long-term ridership?
    - **1.4**: Could this “induced ridership” be considered during decision-making as a qualitative criterion or as part of passenger forecasts?
- **Question 2**: How can this knowledge help decision-making? Is it worth considering those benefits during the decision-making process, or the more traditional benefits (travel time and traffic reduction) are enough?
- **Question 3**: What means the sense of permanence?
- **Question 4**: Can we achieve a sense of permanence, and its associated benefits, with road service or only with rail service?

To help answer these questions, a methodology framework was developed and is briefly presented in the next section.

1.4. Research methodology

The methodology framework for this study is divided in three phases: **Observe**, **Understand** and **Intervene**. In the first phase, **Observe**, a structured literature review of the following fields was performed:

- capital investment decision-making on public transport systems;
- land use and transit decision-making;
- decision parameters and aspects that are relevant in this context;

- BRT and LRT;
- accessibility, land use and transport interaction (LUTI) and LUT models;
- DSSs and appraisal methods: CBA, MCDA, sensitivity and risk analysis;
- interviewing and opinion surveys methods.

The second phase, **Understand**, comprises the major contributions of this research to society, being the most relevant part of this research. The objective of this phase is to provide a deep understating of the relations at a disaggregated and more detailed level. To achieve that, a DSS, combining a “straightforward” LUT model (Meyer and Miller, 2001) with a MCDA model (Vincke, 1992), was developed and assessed in a small case study and in a real case study (the Green Line Extension Project in Boston, Massachusetts, the USA). Although the system has a more general scope, this instance was configured to focus on BRT and LRT systems, as they are comparable to a certain degree (Vuchic, 2007; Wright and Hook, 2007). Still in this phase, some public transport experts were interviewed, to understand what is the level of consideration that should be given to each decision parameter. Finally, the **Intervene** phase consists of delivering the final thesis report and the DSS. Table 2 presents the methodology framework.

In this framework, item 1.1 reviews BRT and LRT systems. 1.2 and 1.3 cover the state of the art and practice regarding decision-making, while 1.4 and 1.5 review how land use changes are modeled, forecasted and evaluated. 1.6 and 1.7 review how the decision-making process is structured, typically starting with the definition of investment alternatives, modeling, forecasting, evaluation, sensitivity analysis and final decision. All these items are covered in chapters 2 and 3.

The development of the DSS (items 2.1, 2.2 and 2.3) consists: in designing a “straightforward” LUT model, to foster the incorporation of land use changes (which are sometimes ignored due to the complexity of state of the art LUT models); the development of a MCDA model, as such models are more adequate to evaluate land use changes than CBA; and, finally, a survey with public transport experts to gather the views and opinions for the MCDA weights. Chapter 4 presents the DSS. Still in chapter 4, a small case study is developed and assessed with the DSS. Later, the DSS is tested in a real decision problem, the GLX project, under construction in Boston, the USA.

Table 2 - Research methodology

1. OBSERVE	Structured literature review: State of the art, State of the practice	1. BRT and LRT. 2. Capital investment decision-making on public transport systems. 3. Decision parameters and aspects. 4. Land use and transit decision-making. 5. Accessibility, LUTI and LUT models. 6. DSSs and appraisal methods: CBA, MCDA, sensitivity and risk analysis. 7. Interviewing and opinion surveys methods.
2. UNDERSTAND	Development of the DSS	1. A “straightforward” LUT model. 2. A MCDA model. 3. A survey with public transport experts.
	Small case study development and assessment	1. Development of a “toy problem”; a simple and small case study (5 zones) to test the DSS. 2. This case study will replicate, based on the literature review applied over a generic dataset, the cause-effect relationship between BRT or LRT systems with land use and transport. 3. Various investment alternatives will be analyzed, each with a BRT or LRT system and their respective features: costs; route; station spacing; speed; capacity; frequency; etc. 4. The investment alternatives will be assessed applying the DSS, to choose the best investment alternative, from a set of alternatives.
	The Green Line Extension Project	1. Like the previous process, investment alternatives will be introduced on the transport model developed for the city of Boston by MIT; 2. The investment alternatives will be assessed applying the DSS, in order to choose the best investment alternative, from a set of alternatives.
3. INTERVENE	Final version of the thesis and the Decision Support System	

2. CAPITAL INVESTMENT DECISION-MAKING ON PUBLIC TRANSPORT SYSTEMS

- Introduction
- Definition of investment alternatives
- Common decision parameters and aspects
- Four-step model
- Cost Benefit Analysis
- Multi-Criteria Decision Analysis
- Risk and uncertainty
- The final choice
- Conclusions and further research

2.1. Introduction

When planning a new transportation system or improving an existing one, analysts face several decisions regarding the choices of solutions (e.g. double-decker or articulated buses?) or courses of action (e.g. buy new buses or renovate the old ones?). Normally, depending on the level of complexity involved, decisions may have good or adverse consequences on short and/or medium/long term. Therefore, the process of *decision-making* should be carefully conducted to minimize future negative impacts and maximize possible direct and indirect benefits.

Despite the level of sophistication and precision associated with highly detailed transport models, their results should be considered as a guidance for planning and not necessarily be adopted blindly by the analyst and the decision-makers. Moreover, not all information is available, leading to some level of uncertainty over the results.

Consider the following problem: a rural transit agency owns three buses, each one with a current value of \$5,000. One of them broke down yesterday and must be replaced or become operational as soon as possible. To address the issue, the agency has two main options: buy a new bus for \$10,000 plus the old one, or fix the old bus with repairs costing either \$1,000 or \$5,000. The experienced mechanic believes there are 60% chances the repair might cost \$1,000, and 40% it can go up to \$5,000 (Figure 1). What should the agency do?

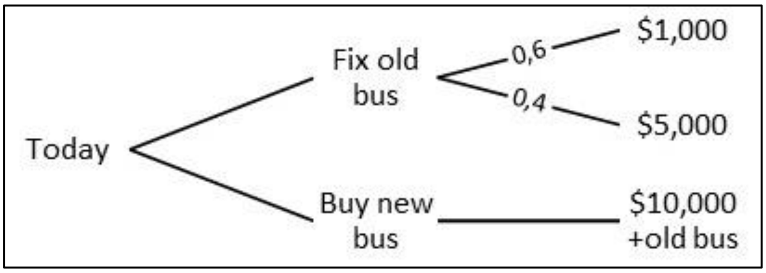

Figure 1 – A decision tree

Such problems may be solved in several ways: the agency can spend more time getting additional information about the outcomes, and improve the decision model (at what cost?); or they can implement single criterion decision approaches by adopting a decision paradigm such as the minimization of the expected value. Since the only item to consider is cost, it is a straightforward decision process that is more related with the risk the agency is willing to take rather than the problem itself. For more complex problems, e.g. capital-intensive projects, more sophisticated and structured evaluation methods and tools must be applied to assist the decision process.

Dror (1968), cited by Meyer and Miller (2001), presents a five-step rational decision-making model that starts by understanding the context for decision-making and weighting societal values and goals, and finishes by selecting the alternative which maximizes the specified goals. UK Gov. (2009) presents a similar six-step process that includes a last feedback stage. Turban, Aronson, and Liang (2005) divide the process in four broad phases named as "Intelligence, Design, Choice and Implementation", and Baker et al. (2001), cited by Fülöp (2005), state that before initiating the process of decision-making, a clear identification of the decision-makers and stakeholders should be made, in order to reduce misunderstanding regarding problem definition, requirements, goals and criteria. Then, an eight-step decision-making process can be performed. Some authors (Clemen and Reilly, 2013; European Commission, 2008; Instituto Nacional de Ecología, 2006; TRB, 2011) also emphasize the importance of a final sensitivity analysis.

Despite the different considerations and highlights, all authors agree that, to help make the decision, some sort of *decision support system, technique* or *aid* should be utilized. The most common techniques in the transportation field are CBA and MCDA. Those techniques can be applied separately or in an integrated way. Hence, a typical decision methodology encompasses the definition of investment alternatives, definition of the decision parameters, forecasting, evaluation, sensitivity analysis and final choice. Figure 2 and Table 3 present this general methodology along with the associated sections of this literature review.

Table 3 - A decision process

Step	Description	Sections
1	Definition of investment alternatives	2.2 Definition of investment alternatives
2	Definition of decision parameters and aspects	2.3 Common decision parameters and aspects
3	Forecasting	2.4 Four-step model
4	Evaluation	2.5 Cost Benefit Analysis 2.6 Multi-Criteria Decision Analysis
5	Sensitivity analysis	2.7 Risk and uncertainty
6	Final choice	2.8 The final choice

This chapter presents a literature review, with the state of the art and of the practice on decision-making for capital investments in public transport systems, i.e. in the construction of new or extended transit systems. Section 2.2 reviews public transport systems focusing on medium capacity solutions such as Bus Rapid Transit and Light Rail Transit. Section 2.3 addresses common decision parameters and aspects, regularly considered in the decision process, followed by the explanation of one of the most widely used methods for estimating those parameters, the four-step model (2.4).

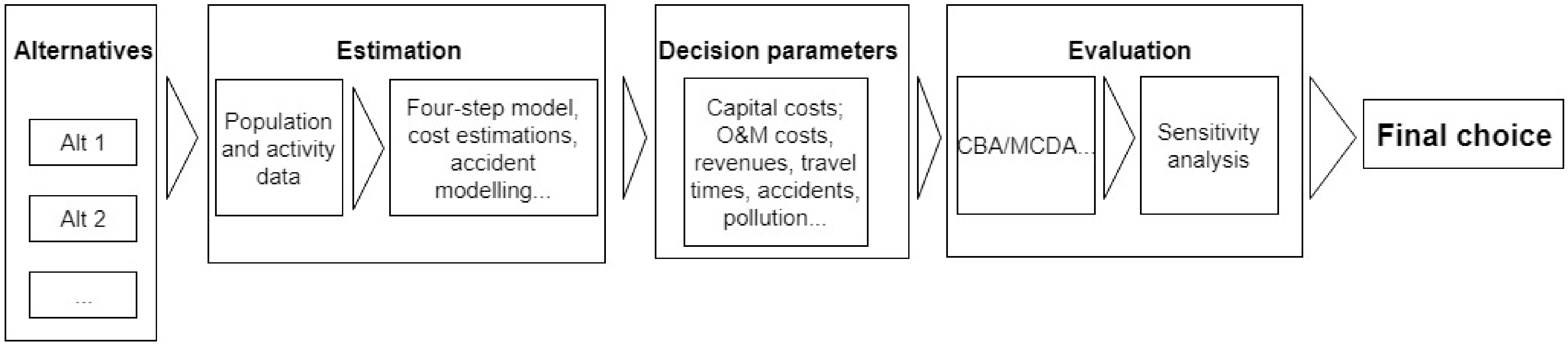

Figure 2 . A decision process

Then, two extensively employed evaluation methods, Cost Benefit Analysis and Multi-Criteria Decision Analysis, are presented (2.5 and 2.6), followed by a section about how to incorporate risk and uncertainty on decision-making (2.7). Before concluding, section 2.8 discusses some drawbacks found in current decision-making that lead to poor final choices, and section 2.9 concludes this first part of the literature review and presents some issues for future research, such as the need of including land use issues on decision-making. The chapter is concluded showing the potential in researching and experimenting new and innovative decision tools based on Multi-Criteria Decision Analysis, mainly when hard to monetize decision parameters, such as accessibility, density, mixed-use and property values, take part in the decision-making process, therefore serving as a complement to traditional Cost Benefit Analysis. These issues will be addressed in the second part of this literature review: Land use and public transport decision-making (chapter 3).

2.2. Definition of investment alternatives

2.2.1. Introduction

For a long time, city managers have been facing a dilemma concerning transportation options. As stated by Vuchic (2007) there was a great need for medium capacity services. Bus Rapid Transit (BRT) and Light Rail Transit (LRT) are two public transport technologies that can be framed as medium capacity solutions. Despite some different visions regarding the details, researchers (Cain et al., 2006; ITDP, 2013; TRB, 2012; Vuchic, 2007; Wright and Hook, 2007) generally agree that those two systems need some level of segregated Right-of-Way (ROW) to achieve a good overall system performance (Figure 3).

According to Vuchic (2002) there are 3 categories of ROW: A, B and C. ROW C represents urban streets with mixed traffic. In category ROW B, transit systems are partially separated from other traffic but have crossings at grade; and ROW A comprises all transit systems that are totally grade separated, such as underground subways and elevated rail systems. Added to the physical segregation schemes described, traffic lights coordination and Intelligent Transportation Systems can improve system performance by reducing travel times (Wright and Hook, 2007). Despite this classification in three ROWs, the frontiers are not always that clear, and sometimes solutions are somehow in between, containing some features from one category or another.

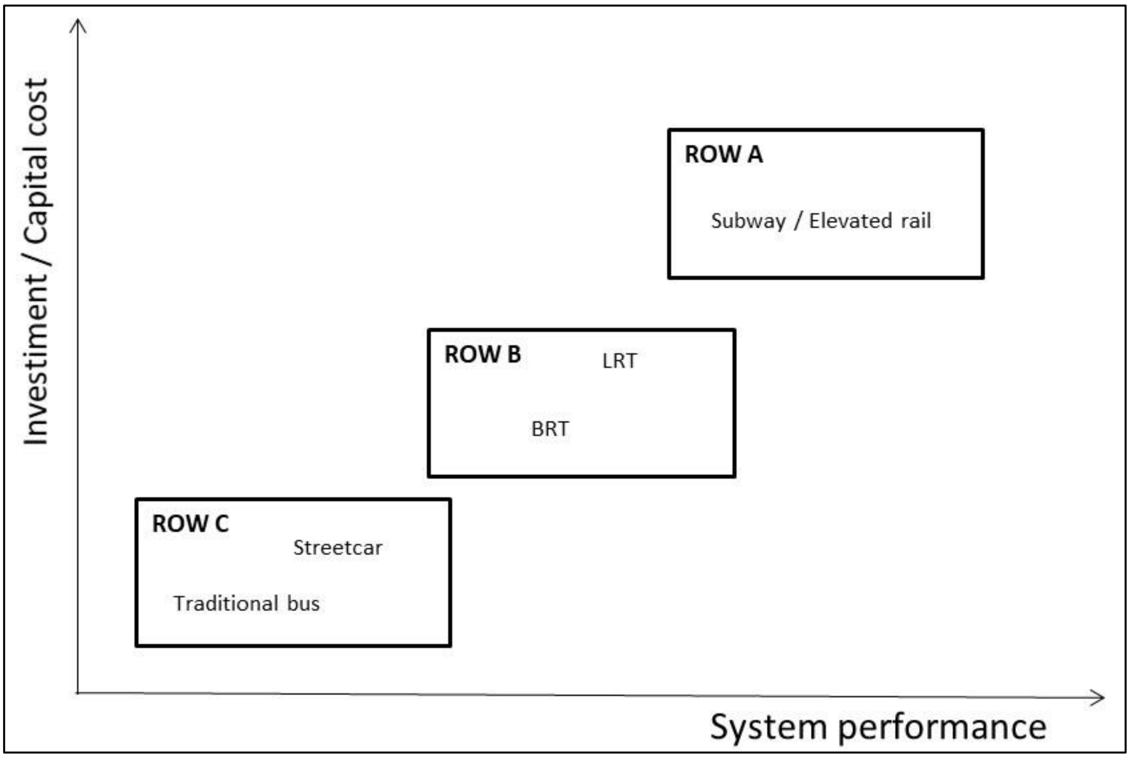

Figure 3 - ROW, system performance and costs (Source: Vuchic, 2007).

As stated by Deng and Nelson (2011), BRT is an emerging form of mass transit, tying the speed and reliability of rail service with the operating flexibility and lower cost of conventional bus service. The development of BRT systems became a cheaper and viable alternative to rail modes, mainly competing with LRT systems. Table 4 shows a comparison between the main transit solutions available and their most common features (based on Cain et al., 2006; De Bruijn and Veeneman, 2009; Deng and Nelson, 2011; TRB, 2012; Vuchic, 2002; Wright and Hook, 2007).

Table 4 shows various relevant features of four major transit systems. Considering capacity, speed, ROW and headway, BRT and LRT are the most similar. Both can deliver medium capacity solutions with good speed and headway; however, a BRT tends to generate more local pollution and gives a less sophisticated image to the city. Concerning capital costs, BRT's capital costs are lower than LRT's: according to Wright and Hook (2007), BRT can be four to 20 times cheaper than LRT. Regarding operating costs, Vuchic (2002) states that LRT can have smaller costs due to economies of scale, generated by large vehicles and train operation.

The capacity of transit systems can be measured by the number of passengers per hour per direction (pphpd) transported. The capacity range of BRT systems is significant. Some European and American systems, with some mixed-traffic operations and regular buses, present capacities ranging from 3,000 pphpd to 6,000 pphpd (Kerkhof et al., 2011). Other South American and Asian

Table 4 – Comparison of systems

Features	Transit Systems			
	Conventional bus services	**Bus rapid transit (BRT)**	**Light rail transit (LRT)**	**Subway/ elevated rail**
Capacity (pphpd) (1 lane)	Low: 500-5k	Medium: 3-15k	Medium: 6-26k	High: 30-80k
Speed	Slow	Medium	Medium	Fast
ROW	Mixed with traffic	Partially separated	Partially separated	Totally separated
Headway	Medium-Long	Short-Medium	Short	Short
Support	Roadway	Roadway	Steel track	Steel track
Guidance	Steered	Steered/Guided	Guided	Guided
Vehicle control	Visual	Visual	Visual/Signal	Signal
Vehicle propulsion	Internal combustion	Internal combustion	Electric	Electric
Vehicle capacity	120	160-260	170-280	250
Vehicle combination	1	1	1-4	4-10
Construction time	Fast	Medium	Slow	Very Slow
Capital cost	Low	Medium	High	Very High
Operating cost	Low	Medium	Low-Medium	Low-Medium
Local emission	Medium	Medium	Low	Low
System image	Low	Medium	High	High
Passenger attraction	Low	Medium	High	High
Impacts on land use and city livability	Low	Medium	High	High

systems, such as Curitiba, Porto Alegre and Guangzhou, can have ridership between 10,000 pphpd until 30,000 pphpd (Hook, 2008). Bogotá, as a unique case, reaches 45,000 pphpd mainly because it has, in almost all the routes, two reserved lanes each way (Gilbert, 2008), multiple stopping bays and an average speed up to 30km/h. As stated by Hook (2008), no matter how big the vehicles are, BRT can only reach 15,000 pphpd with only one lane per direction.

Another advantage of BRT when compared to LRT is the flexibility to improve when more capacity is needed, possibly by converting the system into a LRT (Henke, 2013; Rathwell and Schijns, 2002; Wood et al., 2006). And also to branch out bus lines off the busways, such as in Guangzhou, Brisbane and Ottawa (Hidalgo and Gutiérrez, 2013; Rathwell and Schijns, 2002). Because of the "poor image" normally associated with the bus, some experts (Vuchic, 2002) believe that BRT's impact on land use can almost be negligible. Lacking the "sense of permanence" (Currie, 2006), usually associated with rail systems and rail tracks, weakens the perception of benefits derived from this kind of transport system. The "excessive versatility" of the bus systems (i.e. very easy to change routes, stops and schedules) can rather create a “sense of instability” and reduce the interest in land development near bus stops and stations. In a way that is different from a bus service on a road or street, rail tracks give a more integrated “system-like” impression, a reason for promoting rail services. On the other hand, the LRT infrastructure cannot be easily removed in case of misplaced investment or ridership losses, thus it is very important to couple rail investments with local urban development incentives, e.g. TOD (to be discussed further on). Cities such as Cuiabá (Brazil) and Malaga (Spain) fail to do that, but this is not the case of many European cities that successfully integrated land use and rail development. Integration can be divided in three major areas (Wright, 2004):

- modal integration;
- land use integration;
- travel demand management.

Modal integration comprises all the other transport modes that can connect with a BRT or LRT system in a station. Weather-protected pedestrian access, connection with cycle paths and *Bike-and-Ride* facilities; *Park-and-Ride* facilities mainly in suburban stations; a station layout that allows fast and comfortable transfers between feeder buses and trains; and, finally, connection with taxi services, are the main characteristics of a good modal Integration scheme. This kind of integration can also extend beyond just being physical and have integration of fares (e.g. same ticket for parking and public transport) and information (crossing multiple systems data concerning departures and arrivals, travel time, speed, delays, parking availability). European BRT, also known as Bus with High Level of Service (BHLS) (Heddebaut et al., 2010), and LRT systems have a strong “integration tradition”, when compared to similar solutions in other countries. A strong trend — intermodality with cycling – can be observed in the Netherlands, Sweden and the UK, so that many stations have some space dedicated for *Bike-and-Ride* (Kerkhof et al., 2011). In Almere, the Netherlands, this “integrated system approach” is very clear with a BHLS system strongly integrated with bikes, P*ark-and-Ride*, train stations, and urban development.

Land use integration may also be viewed in the context of as TOD (Transit Oriented Development). TOD[3] is an urban design and public transport combination that aims at improving the effectiveness

[3] The TOD concept and TOD plans are discussed in detail in section 3.3.

of transit as well as supporting community goals and improving accessibility (Cervero et al. (2004) cited by Currie (2006)). Proximity to mass transit can save time and money from commuting, properties near transport facilities generally become desirable for new development or redevelopment (Deng and Nelson, 2011). For BRT systems, solutions such as the one in Curitiba (high density residential and commercial development along the corridors) show the true advantage of orienting land development nearby BRT stations and corridors, or even in the whole city. Connection with shopping malls or hospitals can greatly increase transit ridership.

Travel demand management is based on set of policy measures that discourage automobile use or promote public transport ridership. Some common measures are (Wright and Hook, 2007): reduction in parking supply; increase in parking fee and enforcement; circulation restricted by license number; congestion charging and road pricing; traffic calming measures. These three subjects (modal integration; land use integration; and travel demand management) can be handled together or separately. Normally more Integration measures lead to better transport planning.

BRT and LRT are having a growing role on the future of cities. To cite just some recent and current undertakings: in Brazil a new BRT in Belo Horizonte; and LRTs in Santos, Rio de Janeiro and Cuiabá (globo.com, 2015). China, among other countries, have also launched or upgraded, during the last decade, 16 BRT systems with various configurations and features (Deng et al., 2013; Global BRT Data, 2013; Hidalgo and Gutiérrez, 2013). In the US and Canada, planning and construction of various LRT project are taking place in almost 40 different cities, some of them still looking for funding under federal transit programs (thetransportpolitic.com, 2015) Therefore, there are no doubts about the importance given to BRT and LRT as transit solutions.

2.2.2. Bus Rapid Transit and Light Rail Transit

Bus Rapid Transit (BRT) are mass transit systems. Such as subways and suburban trains, a BRT aims at providing transport capacity and commercial speed that a regular bus service cannot achieve. The precise definition of a BRT system depends on the authors (Deng and Nelson, 2011; Levinson et al., 2003b; Wright and Hook, 2007). Although they generally agree that a BRT is a rubber-tired flexible bus-based system that combines stations, busways, pre-boarding payment and Intelligent Transportation Systems (ITS), with a cost-effective proposal. It puts together the qualities, reliability, medium capacity and speed normally associated to rail systems, with the versatility and low cost of buses. Moreover, another acronym recently emerged in France and in the European bus industry, the BHLS, a BRT inspired by rail performance and adapted to the European urban context (Kerkhof et al., 2011). Basically, a BHLS is a lighter version of a BRT, more focused on reliability and integration, rather than capacity and speed. In the family of tire-based transit systems, BRT and BHLS are the available solutions with best performance.

Light Rail Transit (LRT) are mass transit systems with a longer history than BRT. Their deployment becomes popular after World War II, through Central Europe and the developed world, as the backbone of many urban transit systems. According to the American Transportation Research Board (as cited by De Bruijn and Veeneman (2009)) a LRT is a metropolitan electric railway system characterized by its ability to operate single cars or short trains, along exclusive rights-of-way at ground level, on aerial structures, in subways or, occasionally, in streets, and to board and alight passengers at track or car-floor level. LRT fit in a spectrum of rail transit solutions that can be divided in four types, allowing some overlapping: Streetcar / Tramway; Light Rail Transit; Rapid Transit (underground or elevated) and Regional Rail / Commuter Rail. Being in the middle of this spectrum, an LRT is a versatile option that can be considered as a semi rapid transit system (Vuchic, 2007). Such as a BRT, it demands some level of segregated ROW to properly operate. The main features that distinguish rail systems from other transit solutions are external guidance, rail technology, electric propulsion and ROW separation (De Bruijn and Veeneman, 2009; Hass-Klau and Crampton, 2005; TRB, 2012). Other characteristics associated with LRT are: low floor level; greater, cleaner and more sophisticated appearance when compared to buses; wide body; and higher passenger capacity per driver, because of the possibility of combining several transit units altogether operated just by one driver, thus increasing substantially passenger throughput (Vuchic, 2007).

The reason for creating BRT solutions was the need of a fast, medium capacity, reliable and cheap transit solution, when compared to the rail costs. According to Deng and Nelson (2011), the first exclusive bus lane appeared back in 1937 in Chicago, the USA. Later, the *busway* concept was improved until 1974, when the first proper BRT system was deployed in Curitiba, Brazil.

In fact, this system introduced a set of innovative features, creating, in this way, the Bus Rapid Transit concept. Its key features are (Lindau et al., 2010):

- median busways longitudinally segregated;
- *tube-shaped* stations with fare prepayment and level access;
- physical and fare integration;

- various retail and services at terminal stations;
- dispatch control;
- high capacity bi-articulated vehicles up to 260 passengers/vehicle;
- passenger information inside the vehicles, terminals and tube stations.

Figure 4 - BRT in Curitiba, Brazil and LRT in Porto, Portugal (Source: Wikipedia 2015).

BRT or LRT systems need to have the following main elements (Deng and Nelson, 2011; Hass-Klau and Crampton, 2005; Levinson et al., 2003b; TRB, 2012; Wright and Hook, 2007):

- ROW: busways and railways;
- stations;
- vehicles;
- service configuration;
- system identity and image;
- Intelligent Transportation Systems

2.2.2.1. <u>ROW: busways and railways</u>

Bus runways can be classified in curb bus lanes and in median busways on city streets (Levinson et al., 2003a). There are also reserved lanes on freeways, bus-only roads and corridors, tunnels, and buses on highway shoulders. The most significant factor to substantially improve the quality of the bus service is the level of segregation from regular traffic. Wright and Hook (2007) strengthen the difference between bus lanes and busways regarding the ROW (Figure 3). Bus lanes are widely spread across the world, and can have substantial impact on performance, as for example in the case of London. However, normally when implemented alone in the curb lane without any other priority measures, there will be no significant effect in improving transit service. In a different way, busways are exclusively used by public transport because they are physically segregated from traffic, considerably enhancing the system performance. For BRT systems, the busways can also be painted in a distinct color (e.g. in Castellón), made with regular asphalt (e.g. in Curitiba), or concrete (e.g.in Twente). They can also have some guidance devices like in Rouen with optical guidance; in Cambridge, Adelaide and Nagoya with physical guidance; and in Eindhoven, with magnetic guidance (Kerkhof et al., 2011).

LRT systems, by default, tend to have higher ROW than BRT systems. With an LRT, a rail-based system, it is politically easier to prohibit mixed traffic from occupying the rail corridor. In some sense the most iconic element of an LRT in particular, and a rail system in general is the railway. Rail tracks deployed over the countryside, or in an urban environment, bring a "sense of permanence" and some certainty about a potential transportation service running on that infrastructure. LRT must have some level of segregated ROW to properly operate, allowing general traffic to cross the tracks at signalized intersections, preferably with transit prioritization, i.e. the train should only stop at stations or when an event such as a traffic accident blocks the rail tracks. On the other hand, when such level of ROW is not achievable and thus mixed-traffic can circulate over the rail tracks and there is no signal prioritization for LRT vehicles, the rail option substantially loses performance, due to the inability of changing lanes and overtaking and having to stop at red lights.

2.2.2.2. Stations

Stations are a critical element in achieving system identity and image (Levinson et al., 2002). They are the interface that connects the system with the passengers, and they can have a variety of configurations, from regular open bus/streetcar stops (very common in European systems), to closed pre-board payment stations, with the iconic t*ube-shaped* station of Curitiba. The station layout can be designed to allow multiple docking and passing for express services.

A BRT or LRT station must have good walking / feeder services connections, passenger information, protection from the weather and, if possible, *park/bike-and-ride* facilities. Other essential features are the platform level boarding and efficient vehicle alignment with the station. According to ITDP (2013), those features are important ways of reducing dwell times, allowing faster entering and exiting the vehicles, and enhancing conditions for all passengers. The platform level boarding can be done by using low floor vehicles or elevated stations. For an efficient bus alignment, the solutions vary from very sophisticated guided system, such as in Nagoya and Rouen, to just relying on the bus driver skills. Light rail drivers do not face such issue due to rail tracks guidance.

Figure 5 - BRT station in Curitiba, Brazil and LRT station in Porto, Portugal (Source: Barcex 2011).

The station can be located on the curbside or in a central island between the corridors. The station spacing regularly range from 300 to 1,000 meters (Wright and Hook, 2007). The spacing will also depend on local demand levels, walking conditions and destinations (shopping malls, public services) on the surroundings.

On-board fare collection and verification, very common in traditional bus systems, tend to dramatically increase dwell time and reduce passenger throughputs. Emulating rail systems, off-board fare collection and verification became the standard of quality for BRT systems. Combined with level boarding and alighting, off-board fare collection and verification crucially contribute to the reduction in total journey time and time variability, and lead to less crowding at stations (Hensher and Li, 2012).

Two types of fare collection and verification are mostly used in practice. The first type, very common in Latin American systems, is the *barrier-controlled* system. In this system passengers must pass through a gate or turnstile when entering and, sometimes, exiting the station. The other type, common in the USA and Europe, is the *proof-of-payment* system, where the passenger pays at a kiosk or vending machine and collects a paper ticket or magnetic card, which might be later verified by a random inspection inside the vehicle. ITDP (2013) states that the barrier-controlled system is preferable because it minimizes fare evasion. The data collected by the turnstile upon boarding, and sometimes upon alighting, can be useful in future system planning and evaluation.

LRT are quite different from BRT (that can be viewed as the "*metronization of buses*"), really belonging to the family of rail transit modes and therefore having higher project standards from the outset. For LRT nowadays, stations not offering the amenities found on traditional rail systems are therefore quite uncommon.

2.2.2.3. *Vehicles*

For BRT, the type of vehicles can range from standard buses to articulated or to bi-articulated vehicles with capacity up to 260 passengers (Lindau et al., 2010). Yet, the most common BRT vehicle is the low-floor articulated bus that can carry up to 160 passengers. Diesel is still the main fuel used, but Levinson et al. (2003a) and Kerkhof et al. (2011) recognize a trend towards more environmentally friendly fuels, such as clean diesel, compressed natural gas, liquid petroleum gas, biofuels, or towards the adoption of hybrid-electric vehicles. Moreover, BRT vehicles can have features that improve comfort, speed and safety, such as multiple wide double-doors to allow fast and convenient boarding, wide aisles to provide ease of passenger movement, in addition to having a distinctive design to provide a unique identity (Jarzab et al., 2002).

Figure 6 – Bus with a capacity of 260 passengers, operated in Curitiba.

LRT vehicles, on the other hand, have a higher capacity range, being able to couple multiple transit units, thus easily increasing capacity. Such vehicles are sometimes designed in cooperation with the manufacturer, specifically for each project, and a common configuration with two transit units can easily serve up to 450 passengers. This is quite different from BRT vehicles which are an upgrade from traditional buses. Light rail vehicles are, in fact, adaptations of heavy rail vehicles for traveling through the urban environment. They may operate alone or combined, thus achieving economies of scale by increasing transit capacity without increasing the labor force. Light rail vehicles are also more wide and comfortable than BRT vehicles, and trains in opposite directions can run more closely due to guidance provided by the rail tracks. Light rail vehicles are, in general, more appealing than buses as they have a set of features such as electric powered engines, quietness, riding comfort and low-floor access, that are not so common in buses.

2.2.2.4. Service Configuration

One of the key issues characterizing BRT and LRT is service configuration. There are basically two types of service configuration: trunk-feeder, or direct service. Both BRT and LRT might operate in either configuration type (see Figure 7).

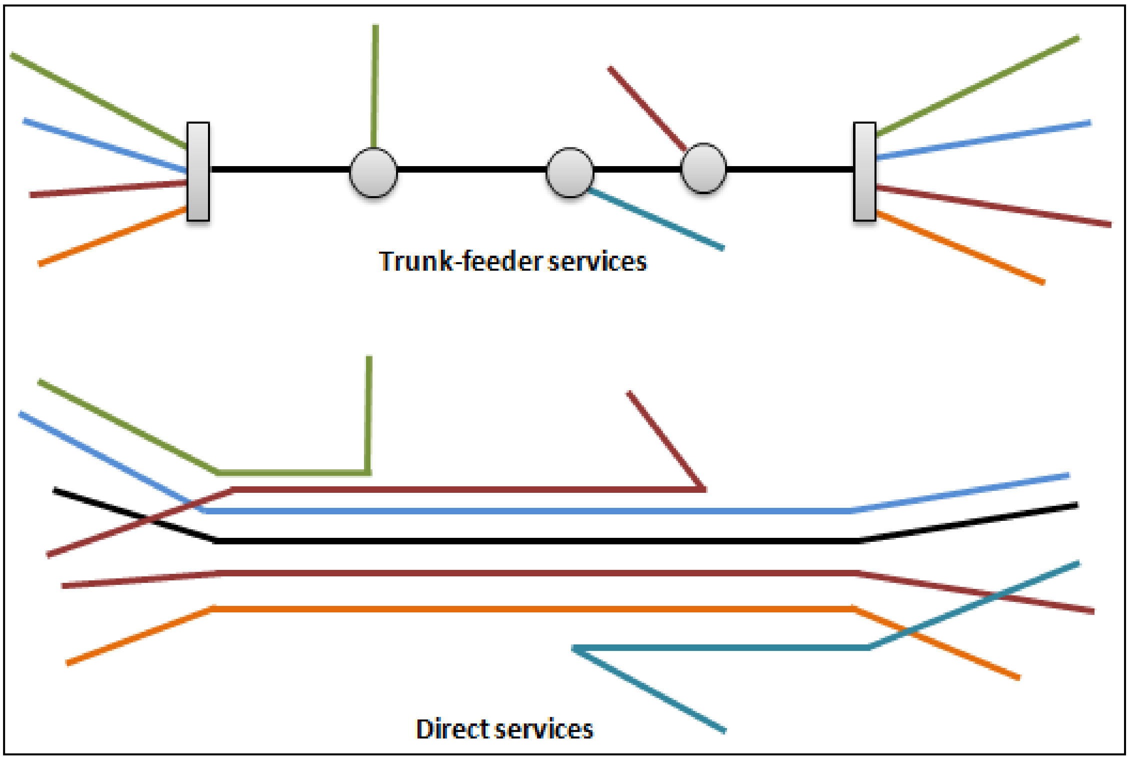

Figure 7 - Trunk-feeder and direct services scheme

Most BRTs operate trunk-and-feeder, using conventional buses in the feeder lines and larger buses in the trunk lines. Passengers must transfer between the trunk and the feeder lines. This service is normally associated to closed systems such as Bogotá and Curitiba, i.e. only certain operators can use the main BRT corridor, normally with a special bus identity and contract. Direct services, however, can reduce the need of transfers, having direct connections to areas outside the main BRT corridor. This type of service is normally found in open systems, such as Guangzhou (Dai, 2011), where any operator can use the busways and stations. According to Wright and Hook (2007), until 2007, most open-type systems have been of somewhat lower quality than closed systems.

Following a tradition of rail systems, LRT systems generally operate direct services, branching out from main corridors to various endings. This is the case of the Green Line in Boston, with 4 light rail lines sharing a common corridor at downtown, thus substantially increasing frequency. LRT trunk-and-feeder services might have traditional buses as feeders as well.

2.2.2.5. System Identity and Image

Identity and image are elements that can be incorporated on a BRT or an LRT system, as key features. Some systems have a strong distinctive image from the rest of the transit network, with their own type of vehicles, corridors, stations, services and fares. They have created a brand, thus making transit riders aware of the differences in service, along with vehicles that are easily differentiated from the standard transit service (Jarzab et al., 2002). Also, aiming at bringing new costumers from cars to public transport, authorities tried different approaches in this area (Kerkhof et al., 2011), varying from specific designed and colored vehicles (BusWay in Nantes, TEOR in Rouen, Trunk Network in Stockholm) to painting bus lanes and busways (almost all UK systems). Another interesting branding solution is found in Las Vegas (ITDP, 2013) with old casino signs at stations.

2.2.2.6. Intelligent Transportation Systems

ITS can be implemented in virtually all components of a BRT or an LRT system. In stations and in vehicles, real-time information about waiting times, next stops and possible intermodal connections can alleviate concerns over the reliability of the service (Wright, 2004). ITS can help the system operation, tracking buses and trains and speed up intersection crossings. Automatic Vehicle Location (AVL) systems locate vehicles on the network, improve dispatch, and allow quicker response to service disruptions and emergencies (Levinson et al., 2003). Traffic Signal Priority systems, such as in Los Angeles (Levinson et al., 2003a) can get up to nine seconds of additional green time when a vehicle arrives at a signalized intersection. Bus guidance systems, another important ITS technology, can be mechanical, optical or magnetic. Other ITS technologies can be applied in fare collection, safety, security, and passenger counting systems.

2.3. Common decision parameters and aspects

A comprehensive literature review led to the identification of a large set of decision parameters and aspects, commonly employed in the decision-making processes, and that can be organized as follows:

- capital costs;

- operating costs;
- ridership / revenues;
- travel time;
- reliability, journey quality, comfort and crowding;
- safety;
- fitness and health;
- environment.

The next sections will discuss these sets of variables and parameters, by presenting their definitions and ways to estimate and evaluate their values.

2.3.1. Capital costs

Capital costs consist of both infrastructure costs and any related land or property acquisition costs. They are the costs related to the deployment of the system and, depending on the procurement strategy, may include vehicles acquisition costs, fare collection and control systems equipment. Capital costs are normally covered by the public sector through grants. Some of the main factors influencing capital costs are (Wright and Hook, 2007; Hensher and Golob, 2008):

- number and length of exclusive lanes / railways;
- materials utilized (asphalt, concrete, rail tracks);
- expected system capacity that influences the size of stations, terminals and depots;
- local construction costs;
- amount of property expropriation required;
- local context of the negotiation;
- number of bidders;
- project financing;
- number of major works such as bridges and tunnels.

The funding recommendations of the US Federal Transit Administration's (FTA) for the financial year of 2017 (FTA, 2016a) proposes 63 projects ranging from *streetcar* to *commuter rail*. Table 5 presents a brief overview on their capital costs.

According to Wright (2004), for the TransMilenio (TM), the BRT system of Bogotá, Colombia, the infrastructure cost division for the initial 37 kilometers are those presented in Table 6. LRT systems infrastructure have a similar cost partition. As shown in Table 6, the total infrastructure cost for the first phase of TransMilenio was US$ 5.4 million per kilometer. Hensher and Golob (2008) analyzed 44 BRT systems around the world and concluded that the infrastructure costs vary from US$ 0.35 million per kilometer in Taipei, to US$ 53.2 million per kilometer in Boston, with most systems costing below US$ 10 million per kilometer.

Table 5 – FTA's funding recommendations for 2017 – Estimated average capital costs

Mode	Capital cost per km (M US$)	Number of projects
BRT	8.7	21
Commuter Rail	18.8	7
HRT	285.8	5
LRT	156.1	16
Streetcar	40.2	7

Table 6 - TransMilenio infrastructure costs (Source: Wright, 2004).

Component	Total Cost (M US$)	%	Cumulative %	Cost per km (M US$)
Trunk lines	94.7	47.3	47.3	2.6
Stations	29.2	14.6	61.9	0.8
Other	25.7	12.8	74.8	0.7
Pedestrian overpass	16.1	8.0	82.8	0.4
Bus depots	15.2	7.6	90.4	0.4
Terminal	14.9	7.4	97.9	0.4
Control center	4.3	2.1	100	0.1
Total	200.1	100	-	5.4

One of the main issues with capital costs is that they frequently overrun (Flyvbjerg, 2007). Before-and-after reports issued annually by FTA (FTA, 2016b) confirm the overruns but shortfalls as well. Despite being a small sample of projects, almost half fail to meet estimated capital costs. Before-and-after reports lack substantial evidence on BRT systems and therefore only findings for LRT systems are shown. Table 7 presents these findings.

Capital costs are measured in monetary units and hence are easily evaluated with CBA.

2.3.2. Operating costs

Operating costs vary considerably depending on the specific system. Some systems are managed within a larger network, and so their operating costs are part of the whole public transport system; others are operated separately, with or without a subsidy. Many systems use private operators, and thus such operators obtain access to revenues from fare collection. Hidalgo (2004) cited by Cain et al. (2006) states that TransMilenio runs without operating subsidies. However Gilbert (2008) argues that TransMilenio benefits from some indirect subsidies, such as cheaper diesel and public security staff for free. Moreover, the comparative assessment performed by Hensher and Golob (2008) with data of 44 BRT systems, shows that Latin American systems are least dependent on operating subsidies than most North American, European and Australian systems. For TransMilenio the operating costs partition, between trunk and feeder services, is shown in Table 8 (Wright and Hook, 2007).

Table 7 – Capital costs misestimation (Source: FTA, 2016b).

Issuing year	Capital cost deviation (%)	Number of projects
2015	0 +26	2
2014	+3	1
2013	+5 -1 -15	3
2011	0 -1	2
2008	+24	1
2007	-6.5	1

Projects revised	10	
Underestimated projects	4	
Overestimated projects	4	

Table 8 - TransMilenio operating costs (Source: Wright and Hook, 2007).

Cost Item	Trunk services	Feeder services
Fuel	24.6%	17.3%
Tires	4.7%	5.2%
Lubricants	1.5%	1.7%
Maintenance	9.0%	10.8%
Wages	14.7%	29.2%
Station services	0.0%	2.6%
Other fixed costs	45.5%	33.2%
Total	100%	100%

LRT systems have a similar cost breakdown, although Vuchic (2002) states that LRT can have smaller operating costs when considering the economies of scale generated by large vehicles and train operation. For the financial year of 2017, FTA proposes 63 projects for funding (FTA, 2016a), ranging from *streetcar* to *commuter rail*. Table 9 presents a brief overview on the operating costs of different modes.

Like capital costs, operating costs may easily overrun. Before-and-after reports issued annually by FTA (FTA, 2016b) confirm the overruns, but shortfalls as well. Despite being a small sample of projects, all fail to meet estimated operating costs. Before-and-after reports lack substantial evidence on BRT systems, and therefore only findings for LRT systems are shown.

Table 10 presents these findings.

Table 9 – FTA's funding recommendations for 2017 – Estimated average operating costs

Mode	Annual operating cost per km (M US$)	Number of projects
BRT	0.95	11
Commuter Rail	0.70	4
HRT	0.43	2
LRT	1.01	9
Streetcar	1.19	7

Table 10 – Operating costs misestimation (Source: FTA, 2016b).

<table>
<tr><th>Issuing year</th><th>Operating Cost deviation (%)</th><th>Number of projects</th></tr>
<tr><td>2015</td><td>+20</td><td>1</td></tr>
<tr><td>2013</td><td>+19
+19
+7</td><td>3</td></tr>
<tr><td>2011</td><td>+14</td><td>1</td></tr>
<tr><td>2007</td><td>-4</td><td>1</td></tr>
<tr><td colspan="3">----------</td></tr>
<tr><td>Projects revised</td><td colspan="2">6</td></tr>
<tr><td>Underestimated projects</td><td colspan="2">5</td></tr>
<tr><td>Overestimated projects</td><td colspan="2">1</td></tr>
</table>

Operating costs are measured in monetary units and hence are easily evaluated with CBA. They are sometimes considered together with maintenance costs, also known as O&M costs.

2.3.3. Ridership / Revenues

Ridership reflects the demand, and can be measured in multiple ways and time periods. Typically, transit agencies annual reports measure ridership as unlinked trips, which are the number of passengers who board public transportation vehicles. Passengers are counted each time they board vehicles, no matter how many vehicles they use to travel from their origins to their destinations (MBTA, 2014). A linked trip, on the contrary, is a door-to-door trip, regardless of transfers between vehicles. Hence, an Origin-Destination matrix presents linked trips.

Regarding capital investment projects, unlinked trips may help estimate transit revenues by multiplying unlinked trips times average ticket price, as each unlinked trip corresponds to a passenger boarding a transit vehicle. Ridership modeling and research show that population density is positively related to transit station ridership, as well as to service headway, integrated networks of routes and corridors, pre-board fare collection and fare verification, and at-level boarding and alighting (Chen and Zegras, 2016; Hensher and Li, 2012; Sung et al., 2014). Many metropolitan areas use *four-step transport models*, built in transportation software such as EMME, Visum and Cube. These models can easily estimate ridership. A step further in this analysis comes from using integrated LUT[4] models (Petersen, 2004) which can estimate ridership accounting for induced land use changes triggered by transportation investment. In the absence of those models, there are more straightforward methods such as discussed in TRB (2006).

Like capital costs and operating costs, ridership might be misestimated. Before-and-after reports issued annually by FTA (FTA, 2016b) confirm overruns but shortfalls as well. Despite being a small sample of projects, almost all fail to meet estimated ridership figures. Before-and-after reports lack substantial evidence on BRT systems and therefore only findings for LRT systems are shown. Table 11 presents these findings.

Table 11 – Ridership misestimation (Source: FTA, 2016b).

Issuing Year	Ridership deviation (%)	Number of projects
2015	-25 +37	2
2014	+4	1
2013	+37 0 -62	3
2011	+19 -14	2
2008	-15	1

Projects revised	9	
Underestimated projects	4	
Overestimated projects	4	

Ridership or revenues can be measured or translated in monetary units, and hence they are easily evaluated with CBA.

2.3.4. Travel time

One objective that has been considered for a long time in virtually all major transport projects is the reduction in travel times. As stated by Metz (2008), in the UK, travel time savings have

[4] LUT models are discussed in detail in section 3.5.1.

accounted for around 80% of the monetized benefits (within a CBA) of major road projects, showing how important this decision variable is viewed. Travel time reduction was, and still is, strongly connected with the perception that people prefer doing something else instead of traveling. The importance of this objective reflects an orientation towards mobility, meaning the easiness to travel (be mobile), instead of accessibility, meaning the easiness to access (reach services and activities).

Litman (2012) states that this mobility orientation that highly values travel time is changing for a more integrated and multimodal approach, that considers accessibility as important as travel time reduction. In fact Metz (2008), when studying travel behavior in the UK over the last 30 years concluded that travel times have increased, showing that people do not travel less. They travel more but faster, with the purpose of accessing more, farther and different services and activities. Those conclusions stress the lower value that, during the last decades, was assigned to other objectives and goals during the decision-making processes. To reduce travel time, the most common way used was to add road capacity, but, if in the long run the benefit of this extra capacity is taken in the form of longer trips to desired destinations made possible by higher speeds, then the detriments — environmental, accidents — could be higher than anticipated.

Despite criticism over travel time savings, researchers and practitioners recognize its importance (Federal Transit Administration, 2016; Mackie, 2008; MacKie and Worsley, 2013; Van Wee and Rietveld, 2008; Wright and Hook, 2007). Certainly being a crucial variable, travel time savings represent the gains in journey times attributed to a new or an improved transit system and just like capital, operating costs and ridership, it is somehow easy to be translated in monetary terms and thus be incorporated on a CBA. Most countries consider the *Value of Travel Time Saving* (VTTS) specified for income, mode and trip purpose, as shown in Table 12 based on MacKie and Worsley (2013).

Recent research on travel time, and more precisely in-vehicle travel time, suggests the use of this time for other purposes rather than just travelling. When a person is not driving, working, leisure, studying are common uses for in-vehicle travel time (Jain and Lyons, 2008; Lyons et al., 2007; Mackie et al., 2001; Mokhtarian and Salomon, 2001; Ory and Mokhtarian, 2005; Wardman and Lyons, 2016). It is also clear that the pleasure of traveling, tourism, fitness and health are associated with active transport modes such as walking and cycling. A future spread of driverless technologies should further promote this discussion, as travel time will not necessarily be a disutility for passengers, after all. Moreover, the perception that users have a daily travel time budget, roughly one hour, and prefer using that budget (Roth and Zahavi, 1981) productively rather than saving that time for other purposes, changes the focus from the trip (i.e. mobility) to the potential destinations (i.e. accessibility). As referred before, many metropolitan areas have *four-step transport models* built in transportation software such as EMME, Visum and Cube. These models can easily estimate travel time. A step further is to adopt integrated LUT models (Petersen, 2004) which can estimate travel times taking into account induced land use changes triggered by transportation investments. In the absence of these models, stated and revealed preference surveys, combined with analysis of historical data and expert opinions might help predict travel time savings.

Table 12 – Value of Travel Time Savings (Source: MacKie and Worsley, 2013).

Country	**Value of travel time savings (€/h)**		
	On business travel	**Commuting**	**Other**
England	39.24	7.43	6.57
Germany	23.50	-	6.3
Netherlands	33.5	9.5	6.5
Sweden	29.13-34.32*	6.25-12.74*	3.89-12.74*
USA	17.63-43.70*	9.20-13.03*	9.20-24.53*
New South Wales – Australia	18.24	10.91	5.55-10.91*
New Zealand	17.60-20.87*	4.11-6.83*	2.67-6.04*

* depending on transport mode, trip length and/or trip purpose

2.3.5. Reliability, journey quality, comfort and crowding

Reliability is, to some extent, a recent concept in the context of capital investment decision-making. It reflects the impact of lateness, delays, congestion, vehicle breakdowns, and other endogenous and exogenous factors, that might disrupt estimated travel time, thus being an effect to consider when assessing travel time savings. Despite its interest, reliability is still mostly dependent on experts' judgments (Eliasson, 2013) as it is quite difficult to estimate it (Eliasson, 2013). However some countries use the standard deviation of travel time as a measure of reliability (Peer et al., 2012).

One reason for incorporating reliability and travel time variability on decision-making is the increasing levels of congestion and delays caused by road accidents. In the case of public transport, there is an ever increasing number of occurrences of vehicles breakdowns and systems failures, as depicted in Figure 8, based on US National Transit Database (NTD) historical data (FTA, 2016c).

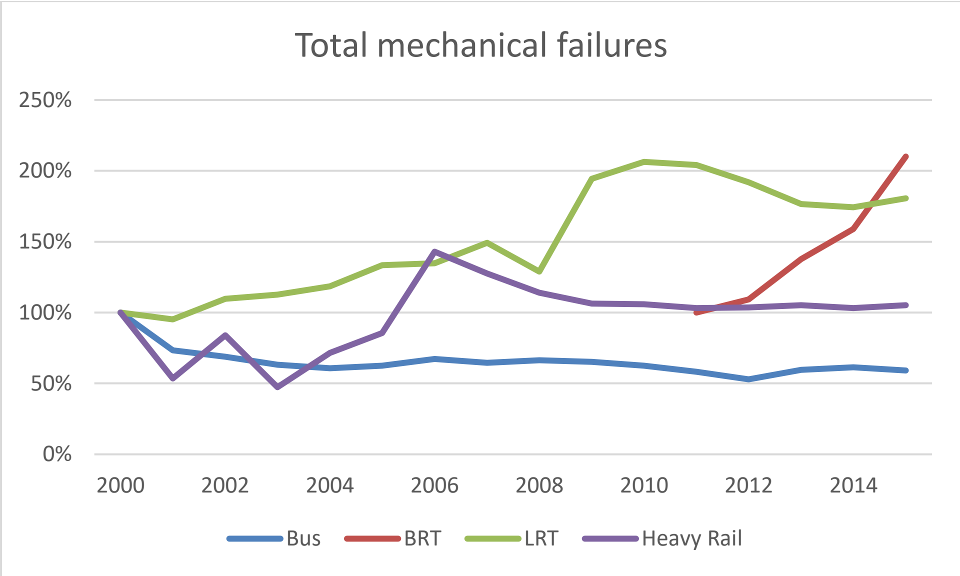

Figure 8 – Total mechanical failures (Source: FTA, 2016c).

Although this data on Figure 8 should be corrected considering a service supply indicator such as vehicle revenue hours or vehicle revenue miles, the figure clearly shows, with an ever-increasing number of failures, why reliability became a major issue in transit decision-making. Just like reliability, journey quality, comfort and crowding are criteria that might affect travel time estimations through penalties, mainly in-vehicle travel time, (e.g. the VTTS of a standing passenger may be higher than a seating passenger) and be indirectly evaluated through CBA. These aspects can also be qualitatively evaluated with MCDA.

2.3.6. Safety

Safety analysis is well stablished in transport decision-making processes, with special focus on accidents and on the *Value of Statistical Life* (VOSL). Table 13 depicts some VOSL figures (MacKie and Worsley, 2013).

By using the VOSL and accident risk modeling, it is possible to estimate the monetary safety gains (or losses) that might accrue from transit and transport capital investment projects and, hence, evaluate it in a CBA approach. Road-based transportation leads to a greater accident risk on its occupants when compared to rail, but rail might increase accident risk to non-users (Litman, 2013a) (see Figure 9). Safety benefits can increase when changing from automobile to transit systems by reducing automobile related accidents. However the barrier effect (Lake and Ferreira, 2002), i.e. the danger of crossing a fast traffic stream, can be considered as a direct cost of transit systems, that require segregated at-level ROW, with solutions such as BRT or LRT.

Table 13 – Value of Statistical Life (Source: MacKie and Worsley, 2013).

Country	Value of Statistical Life (Millions of Euro)		
	Fatal	**Serious injury**	**Slight injury**
England	1.90	0.21	0.02
Netherlands	2.74	0.28	0.01
Sweden	2.80	0.52	0.02
USA	6.98	0.73	0.02
New Zealand	2.43	0.26	0.01

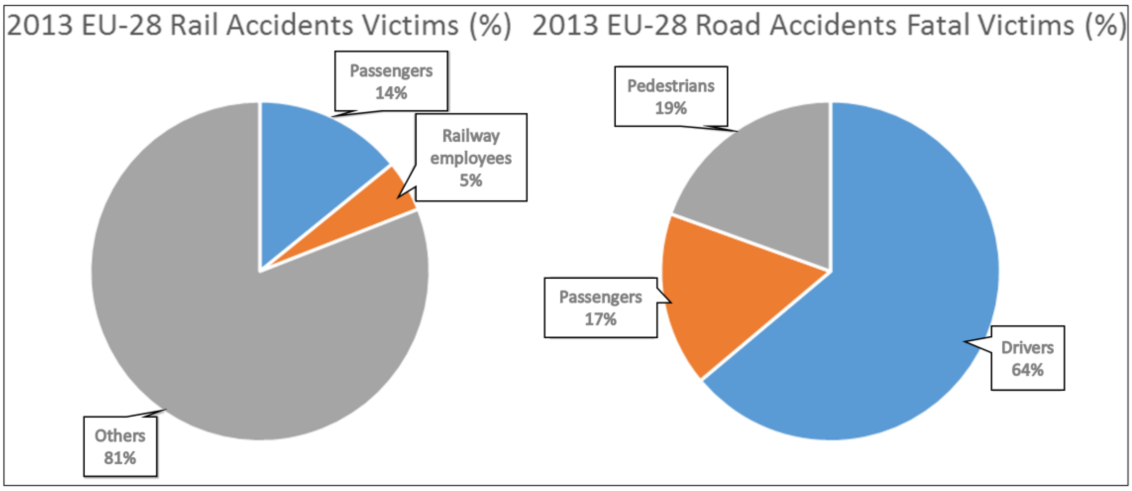

Figure 9 – Road and rail accidents (Source: Litman, 2013a).
Note: Road data is average

2.3.7. Fitness and Health

Recent developments in the impacts of transportation on medium to long-term health and fitness of populations show commuting by car is associated with obesity and other diseases, while walking, cycling and transit are normally related to healthier lifestyles. Fitness and health benefits are not limited to individuals, but rather to the whole society, since less trips by car and more trips by transit, walking and cycling will reduce air and noise pollution and accident risk (de Hartog et al., 2010; Litman, 2013b; Macmillen et al., 2010).

Incorporating fitness and health on traditional CBA is rather difficult as such aspects are hard to monetize. One feasible way is for countries that provide public health care that, in the long run, would benefit from a healthier population and thus decrease health care related expenditures. This approach was pursued by MacDonald et al. (2010), when estimating the public health cost savings resulting from a new LRT system in Charlotte, North Carolina, the USA, concluding that it could save US$ 12.6 million in public health costs over nine years. MCDA is another way to incorporate health and fitness benefits.

2.3.8. Environment

Environmental issues recently became common in transit decision-making processes, recently due to climate changes and growing concerns about developing more sustainable transportation systems for the future. In this review, the environment aspect will cover noise and nuisance effects, air pollution, visual impact, urban environment and the barrier effect. Some of those issues are easy to monetize and fit under CBA whilst other require some sort of qualitative analysis, expert opinion, cost-effective analysis or MCDA.

Noise and nuisance effects are not limited to regular transit operation, and they happen during the construction phase, as well. During this phase, the impacts might noticeably disrupt local urban traffic and livability, and thus are frequent incorporated on decision-making, mainly with the adoption of mitigation and contingency measures, since such nuisance will inevitably happen, even if only for a limited period. In the operation phase, noise and nuisance effects will be felt as long as the system is running, compromising urban livability, and often devaluing property prices near the transit corridors (Hass-Klau and Crampton, 2005). Next to the station, property prices[5] tend to increase, as noise and nuisance effects are allayed by greater accessibility provision. In a recent study, Mulley (2013) quantifies the residential property values uplift around a new-build Liverpool Parramatta busway, in the suburbs of Sydney, Australia. The results show that the BRT system increases house prices when close to the station, but might negatively impact properties when close to the BRT ROW. Due mainly to electric-powered vehicles, rail systems are quieter than road systems, even if recently, changing to quieter hybrid and electric technology was significantly improved this aspect for buses (Litman, 2013a; Vuchic, 2007). Noise can be estimated through noise modeling and feed a CBA in a *willingness-to-pay* per decibel approach (MacKie and Worsley, 2013), ascertained through stated and/or revealed preference surveys.

Air pollution, more specifically greenhouse gas emissions such as Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Ozone (O_3) and Chlorofluorocarbons (CFCs), became a major issue in recent decision-making processes. Such gases can seriously compromise the environment, and are

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[5] This topic is covered at section 3.4.

not limited to local urban cores but might damage global atmosphere as well, causing global warming, a greenhouse effect, and many sorts of pneumonic diseases and cancer. And transportation plays a big role, accounting for 26% of global CO_2 emissions (Chapman, 2007). Rail-based electric systems generally pollute less than road-based internal combustion engine systems, as shown in Table 14 (FTA, 2010).

Table 14 – Emissions (Source: FTA, 2010).

Mode	Emission (grams of CO_2 per passenger km)	Number of transit systems observed
Bus (including BRT)	168	50
LRT	104	30

Note: Estimated average emission of US transit systems.

Many traditional transport modeling software already have greenhouse gas forecasting, as it is the case of EMME and Visum. There is also some literature available on monetary values for greenhouse gas emissions (van Essen et al., 2011).

Much like noise and nuisance effects, visual impacts, urban environment degradation and the barrier effect (caused mainly by bulky transit infrastructure) are subjective and might be reflected on lower property prices. There are basically two ways for considering these aspects on system evaluation: by monetizing it with the help of *willingness-to-pay* for a CBA, or analyzing it with a MCDA or another qualitative approach.

2.4. Four-step model

The decision-making process requires estimating the potential changes a new transport infrastructure or service will cause on the parameters at certain time(s) in the future, for later evaluating them and selecting an investment alternative. The classical *four-step model* (Ortúzar and Willumsen, 2011), comprising trip generation, trip distribution, mode choice and route choice / traffic assignment, is a well-recognized methodology for forecasting some of those potential changes (see Figure 10).

As depicted in Figure 10, before entering the model, population and activity data from the study area must be gathered to define the network. The level of detail of the data varies according to the complexity of the problem, but it is essential to have population, households, jobs and firms for the demand side, and transport network for the supply side. After gathering the data, *Traffic Analysis Zones* (TAZ) (Martínez et al., 2009) must be defined, as they act as origins and destinations in the model. Here, the parameter of analysis is the trip, that is computed, along with all other trips, in an *Origin-Destination* (O/D) matrix.

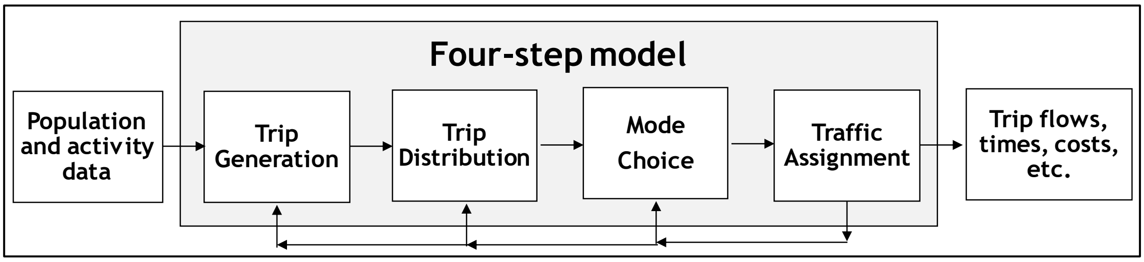

Figure 10 – Four-step model

In the first step (trip generation), the total number of trips generated and attracted by each TAZ is estimated for the period under analysis. This period may, for example, be the AM peak period or the PM peak period. There are multiple ways to perform this step, and a common approach relies on referring to trip generation rates from the Trip Generation Manual (ITE, 2008). More sophisticated methods estimate trip generation through specific trip generation models (Han, 2015). After this step, the borders (i.e. totals) of the O/D matrix will be filled. Depending on the model, the trips might also be divided by trip purpose, income, or type of users: captive users (i.e. they do not change their choice of transport mode) and choice users (i.e. they may change their choice of transport mode).

In the second step (trip distribution), the trips are assigned for each O/D pair, thus filling the core of the O/D matrix. This step can be done by one of two different processes, or by the combination of both: a direct process where surveys about trip origin and destination, frequency and motive are performed with car drivers, transit users, cyclists, pedestrians, among others; and an indirect process typically based on gravity models (either unconstrained models, applied when only trip generation indicators are available, and constrained models, when trip generation at TAZ is known, i.e. when the first step is successfully finished and the O/D matrix totals are estimated).

In the third step (mode choice), the O/D matrix is split among transport modes. This step typically occurs after trip distribution and, hence, it is called trip-interchange model as it splits trip flows (i.e. the matrix core). For some specific cases (e.g. in developing countries, where mode choice is almost completely determined by income and auto ownership), mode choice might be performed prior to distribution (trip-end models). The current state of practice in forecasting trip-interchange mode choice is to use *multinomial logit models* combined with *random utility theory*.

In the fourth step (traffic assignment), all trips are assigned to their transport networks along the most likely path, typically the one that minimizes the travel costs or time, i.e. the *shortest path*. Congestion effects might be overlooked in certain cases, as it is the case for small urban and rural areas, off-peak periods and most transit assignments. In most metropolitan areas where congestion is important, it must be considered in the model. In such cases, travel times and costs might change, and hence earlier steps need to be repeated until reaching equilibrium.

There are several methods and models for each of these steps (for more details see Meyer and Miller, 2001; Ortúzar and Willumsen, 2011). Finally, the outputs produced are evaluated. Common outputs are link volumes, the volume to capacity ratio, transit ridership, the load factor, travel times and the number of congested links. Probably due to their apparent simplicity and straightforwardness, four-step models are largely employed in transportation planning (Ortúzar and Willumsen, 2011). Some criticize the fact stating that four-step models lack travel behavior modeling and connection between trips, hence ignoring their spatial and temporal relationship. It should be noted that four-step models are strongly based on maximizing traveler utility, whereas other factors play a role on defining transport choices such as household dynamics, information levels, parking availability and choice complexity. New approaches such as activity based models try to address some of these issues (Axhausen and Garling, 1992; McNally and Rindt, 2007).

2.5. Cost Benefit Analysis

CBA is an economic appraisal technique employed in transportation decision-making processes and in other sectors. Essentially, CBA monetizes all costs and benefits associated to a transport project or policy. A given point in time is chosen for considering all the amounts, as costs and benefits occur in different points in time (e.g. capital costs can be amortized in periods up to 30 years and travel time savings can be noticed immediately) thus allowing an estimation of the *Net Present Value* (NPV) or the *Benefit/Cost Ratio* (BCR) or the *Internal Rate of Return* (IRR). CBA differs from a simple straight financial appraisal in the sense that it analyzes the impacts (costs and benefits) over all stakeholders affected by a project and not only the project owner. Hence it is also known as Social Cost and Benefit Analysis (SCBA).

The traditional formulation of a CBA is presented below, using a simple Net Present Value (NPV) approach:

1. compute all benefits and costs of alternative projects in equivalent monetized values, if possible at shadow prices (i.e., at prices that better reflect the real costs of inputs to society, and the real benefits of the outputs);
2. determine the Net Present Value (NPV) of each alternative by adding up the discounted net benefits (i.e., benefits minus costs) for the project lifespan;
3. choose the solution having the highest NPV > 0, with

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{1}{(1+r)^t}(B_t - C_t) + \frac{1}{(1+r)^T} S_T$$

where T: project lifespan; B_t: estimated benefits in year t; C_t: estimated costs in year t; S_T: salvage (or residual) value of the project; *r:* discount rate - the rate at which values are discounted.

The formulation and statements above raise some issues worth being discussed. Together with the NPV, BCR and the IRR are the CBA indicators traditionally used to evaluate the economic performance of each alternative project. The BCR is the NPV of project benefits over the NPV of project costs. A project is accepted if the BCR is equal to or greater than 1. The IRR is the discount rate at which a stream of costs and benefits has an NPV of 0. These indicators may be benchmarked in order to evaluate the performance of the proposed project, and the choice of the specific indicators to use is up to the decision-maker and the analysts. The CBA is largely and successfully used in transportation decision-making in countries such as the UK, Japan, France, Germany, the Netherlands and Sweden, occasionally combined with MCDA (Ambrasaite et al., 2011; Douglas and Brooker, 2013; European Commission, 2014; European Conference of Ministers of Transport, 2001; Weisbrod, 2013; Gühnemann et al., 2013; Jong, 2013; Layard and Glaister, 1994; MacKie, 2010; MacKie and Worsley, 2013; Morisugi, 2000; Quinet, 2000; van Wee, 2012).

The main criticism on CBA for aiding transport decision-making is related to its rather strict focus on costs and benefits that are easy to monetize (Beukers et al., 2012). CBA focus too much on hard/tangible effects that are easy to estimate and monetize, such as capital costs, operating costs and travel time savings, “dominating” the “soft” or intangible effects such as livability, real estate gains or losses, quality of nature, accessibility, walking, distributional and agglomeration effects (Damart and Roy, 2009; Eliasson, 2013; Lake and Ferreira, 2002; van Wee, 2012) as well as changes induced by transport improvements to the population, economic activities and land uses (May et al., 2008; Douglas et al., 2013). Although one can always argue that by adopting a willingness-to-pay approach, based on stated preference surveys, *everything can be monetized*, some impacts may not be easily translated into monetary units and this translation should not be done at all (Beukers et al., 2012). Such impacts should therefore be analyzed through a more qualitative approach. Moreover, the costs for acquiring and modeling willingness-to-pay can be burdensome and not necessarily lead to reliable results.

Another question raised by some authors (Manaugh, 2013; Martens, 2011; Thomopoulos and Grant-Muller, 2013; van Wee, 2012; van Wee and Molin, 2012) is the equity issue and its ethical implications. Ignoring negative impacts on some stakeholders who might not benefit from a project, letting negative impacts fall on non-users, or breaking down value of travel time savings by income, are equity and ethical implications found on current CBA. The first case can be exemplified with concerns about environmental justice (Kennedy, 2004) as emissions produced by car users might affect the health of non-car users. The second situation is common, for example, when an elevated highway is built over a poor neighborhood that creates a barrier effect and only benefits cruising traffic, hence ignoring the neighborhood's transportation needs. Finally, the last case refers to travel time savings, as this criterion is responsible for most direct monetized transportation benefits on the current appraisal practice (Metz, 2008). The value of time of higher income groups is higher than that of low income groups, thus, higher income groups score better in a CBA than lower income groups. This situation can be addressed by adopting a single value of time for all, based on an average income level (Martens, 2011).

Nevertheless, CBA will probably continue to be considered as a sound and useful evaluation method even though its role may be minor as political interests mainly behind major infrastructure projects (Eliasson, 2013) substantially influence investment decisions. The Roads of National Significance in New Zealand, have in general low estimated BCRs but are labeled as a project of "national significance" thus securing funding (Douglas et al., 2013). Similar observations by Eliasson (2013) and Mackie and Preston (1998) reinforce the political agenda undermining CBA results. When politicians are committed to a project, a negative CBA result will have less importance, and such projects may be hard to discard because of the degree of political commitment they have gathered.

2.6. Multi-Criteria Decision Analysis

MCDA considers a variety of objectives (criteria) with a set of associated weights. There is a considerable amount of different methods within MCDA that can be divided in three broad categories or schools of thought (Belton and Stewart, 2001; Vincke, 1992): multiple attribute utility theory; outranking methods; and interactive methods. Considering that all MCDA methods have their own specificities, disadvantages and advantages, for the purposes of this work, a very common multiple attribute method used in transportation decision-making will be presented. The steps of this approach are:

1. define criteria to assess the alternatives (as shown in Table 15) – the criteria can be quantitative or qualitative;
2. establish a decision matrix with the objectives / criteria and the alternatives (solutions), defining their relative weights (i.e., the importance of each criterion to the overall performance of the project) (w_j), the value of the solutions in terms of the criteria (x_{jk}) and the type of criteria (benefit or cost) (B/C) (Table 15 presents a hypothetical decision matrix);
3. normalize the decision matrix, i.e., convert the values (x_{jk}) into adimensional figures in the [0,1] interval. Expression such as the following can be used to perform a linear normalization:

$$u_{jk} = \frac{x_{jk} - \min . x_k}{max . x_k - min . x_k}$$

4. The normalized figures give the highest value in the [0,1] interval to the highest benefits (for the costs the results must be subtracted from 1, in order to have the highest values for the lowest costs);
5. compute the “values” of the alternatives through a simple weighted sum, and choose the solution with the highest value:

$$V_k = \sum_j w_j . u_{jk}$$

Table 15 - Decision matrix

	Criteria	**Weight profile (%)**	**Alternatives**			**Type**
			BRT	LRT	MRT	
1	Travel time savings (10^6 min)	w_1	x_{11}	x_{12}	x_{13}	B
2	Daily ridership (pax.)	w_2	x_{21}	x_{22}	x_{23}	B
3	Emissions reduction (tons CO_2)	w_3	x_{31}	x_{32}	x_{33}	B
4	Capital and Operating Costs (million US$)	w_4	x_{41}	x_{42}	x_{43}	C

The normalization process produces a set of so called value functions. Typically, there are two major types of value functions: linear and exponential functions. Figure 11 depicts an example for a capital costs criterion, ranging from US$ 5 million to US$ 65 million.

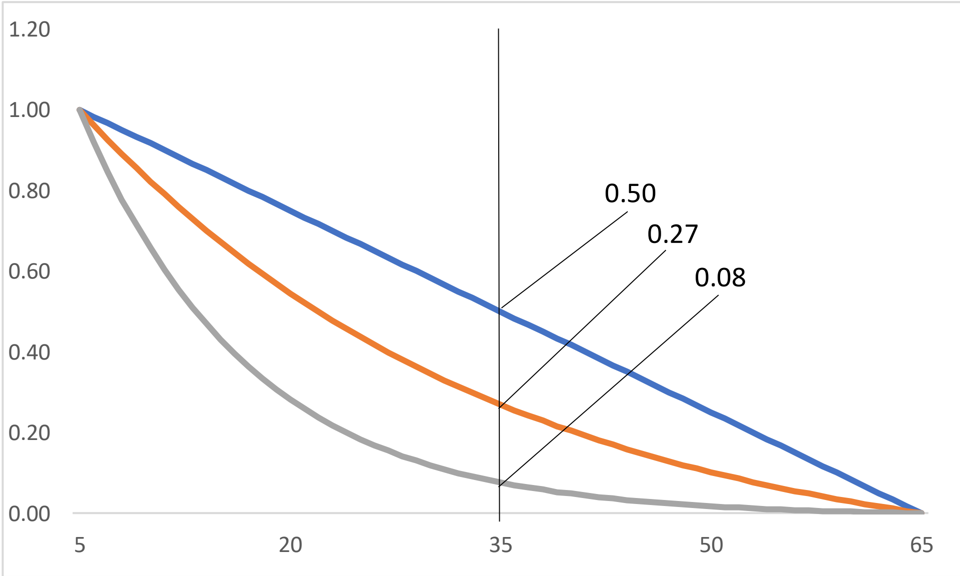

Figure 11 – Linear and exponential normalization functions

On Figure 11, US$ 35 million of capital costs will have normalized values of 0.50, 0.27 and 0.08 for a linear and exponential functions, respectively. On the linear option, the decision-maker equally values a change from 5 to 35, and from 35 to 65, while on the exponential functions the decision-maker might not value equally the same amount of change. E.g. he might value more a capital cost reduction from 35 to 5 than from 65 to 35, even if both reductions are 30. Moreover, in a linear function, there is not a preference towards better values, as it is the case of the exponential functions. The two exponential functions reflect a preference towards smaller values, i.e. the cheaper alternatives. For constructing the value functions, the thresholds for the criteria must be defined. In the example, the thresholds are US$ 5 million to US$ 65 million for the capital cost criterion. Good practice recommends using current market values for the definition of the upper and lower limits.

Finally, weights must be incorporated into the value functions. There are multiple ways for doing this depending on the MCDA technique adopted: the Analytical Hierarchy Process (AHP) (Banai, 2006a, 2010; Saaty, 1987; Thomopoulos and Grant-Muller, 2013); Technique of Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 2012); Measuring Attractiveness through a Categorical Based Evaluation Technique (MACBETH) (Bana e Costa and Vansnick, 1994); Elimination and Choice Expressing Reality (ELECTRE I, IS, II, III, IV, Tri) (Labbouz et al., 2008). All these methods guide the decision-maker throughout the entire process, not only in the weight definition phase.

A criticism on MCDA for aiding transport decision-making has to do with its high degree of subjectivity allowing arbitrary decisions at the will of the decision-makers (Ambrasaite et al., 2011). This often leads to a waste of public funds on projects with high weights on criteria, such as local development effects, that were subjectively estimated or not estimated at all (Quinet, 2000). Moreover, MCDA is often criticized as it provides room for manipulations and double-counting, and lacks robustness (van Wee, 2012; van Wee and Roeser, 2013).

On the other hand, MCDA is widely used in transit decision-making (Camargo Pérez et al., 2015) often combined with CBA or other economic appraisal method (Gühnemann et al., 2013; Ambrasaite et al., 2011; Douglas and Brooker, 2013; European Commission, 2014; European Conference of Ministers of Transport, 2001; Jong, 2013; Weisbrod, 2013; Layard and Glaister, 1994; MacKie, 2010; MacKie and Worsley, 2013; Morisugi, 2000; Quinet, 2000). MCDA has many advantages such as its inclusiveness (Weisbrod, 2013), as it can easily handle relevant issues that are not incorporated or are miscounted in CBA, such as ethical aspects (van Wee and Roeser, 2013), equity, sustainability, induced land use changes, nature or landscape effects, distributional and wider economic benefits, and other hard to monetize criteria (Damart and Roy, 2009; Geurs and van Wee, 2004; Eliasson, 2013; Lake and Ferreira, 2002; May et al., 2008; Douglas et al., 2013; van Wee, 2012). Decisions involving multiple objectives and points of view, as it is the case of problems faced in urban transportation (Camargo Pérez et al., 2015; Damart and Roy, 2009) fit in general, very well on a MCDA approach.

2.7. Risk and uncertainty

Uncertainty and risk are present in all levels of transportation planning, from important long-term strategic investment decisions, such as extending or building a mass transit line, to short-term decisions, such as the daily assignment of drivers or vehicles. How can we anticipate negative outcomes and prevent them to happen? Could we predict costs increasing from US$ 2.6 billion to US$ 24 billion in the Big Dig project in Boston (Flint, 2015)?

However, the two methods described above (CBA and MCDA) do not have uncertainty and risk explicitly built in. They help transport analysts assess proposed investment alternatives but do not have an endogenized way to address uncertainty and risk. It must be the analyst to incorporate on the process his understanding about possible scenarios and outcomes. It is common to distinguish between risk and uncertainty, with risk having a known probability associated to the different possible events, and with uncertainty an unknown probability associated with. In this work, “uncertainty” is used as a general term for describing situations that are non-deterministic and thus can affect final outcomes. A way to model uncertainty is first considering the decision parameters / aspects (e.g. travel time, accidents, costs) as a range of values or value intervals rather than point estimates, and then perform sensitivity analysis and build multiple scenarios (e.g. optimistic, pessimistic).

Modeling uncertainty can be done based on known probabilistic distributions, or on expert judgements. Expert judgements are the simplest and most straightforward way to consider uncertainty, with no need for probabilistic distributions but with the involvement of experts who can propose “structured futures” (Matos, 2007). Probabilistic distributions, on the other hand, are a way to build robust scenarios and interval modeling, that can be backed on statistics. These two main approaches help the analyst build risk profiles and model preferences (risk seeking, averse, and neutral). The definition of these profiles is somehow subjective, and counts on the decision-maker experience and sensitivity to the variables at stake. That is one of the reasons to have multiple decision-makers or stakeholders, with different views and risk profiles. After this first step, a sensitivity analysis and scenario testing should be performed.

Sensitivity analysis tries to respond to questions such as what makes a difference in the final decision, or how can we change the final decision or outcomes (Clemen and Reilly, 2013). It aims to “doubt” the entire process and rethink assumptions, inputs, methods applied and understand if we are solving or trying to answer the right problem. Instead of asking “How can we reduce automobile travel times?” we may ask “How can we reduce automobile traveling?”. “What may happen / what if” are fundamental questions one should ask when performing sensitivity analysis.

The basic approach to sensitivity analysis is keeping all inputs fixed, but one or two. The parameter input is then changed to assess the disturbance caused on outputs and on the outcomes. An effective way to understand these effects is with Tornado plots, that provide a very intuitive, easy-to-understand outlook of sensitivity analysis.

Consider the following example: a small bus network has a current market share of 22%. Boarding time takes, an average, 30 seconds, the stops are 350 meters apart, the headway is 20 minutes, the fare is US$ 1, and the speed is 40km/h. The transit agency wants to estimate the impact on the market share of decreasing and increasing in 50% these different features (Figure 12).

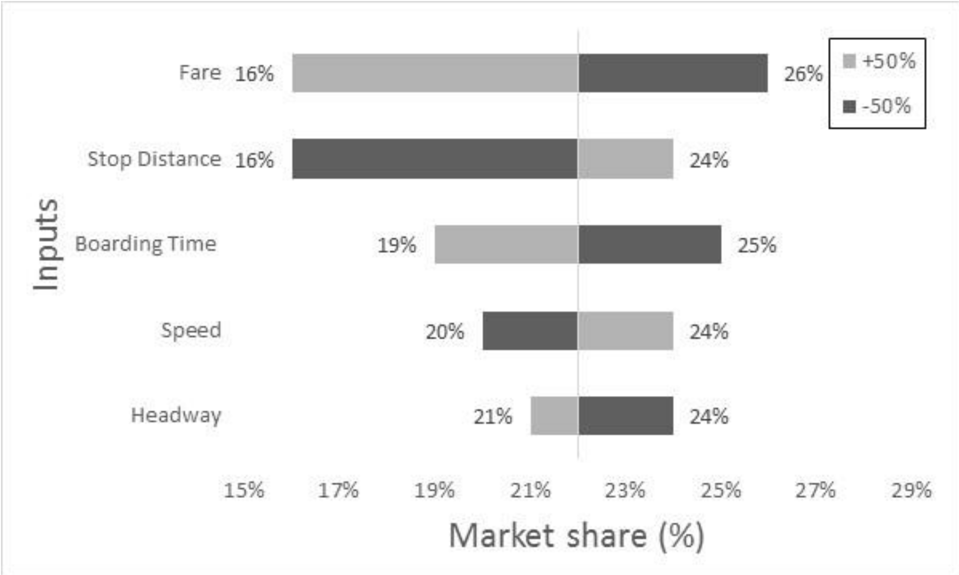

Figure 12 - Tornado plots

Among other aspects, the tornado plot shows that, by increasing fare prices from US$ 1 to US$ 1.5, the market share will decrease from 22% to 16%. On the other way, decreasing boarding time from 30 seconds to 15 seconds, will increase the market share, from 22% to 25%.

The range of variation on the inputs can be based on the uncertainty felt by the decision-maker and other stakeholders, or by relying on probabilistic distributions as described before. The inputs can also be "tried out": some pessimistic and optimistic scenarios, results from public participatory meetings or randomly, through Monte Carlo simulation (Ambrasaite et al., 2011). In summary, sensitivity analysis should be viewed as a source of guidance in modeling a decision problem (Clemen and Reilly, 2013). It helps finding the right decision model, and tune it to tackle the issues at hand, and to understand why a certain alternative should be chosen.

Some outputs may seem to be less strong and more susceptible to uncertainty than others. Among these outputs, capital and investment costs regularly deviate from original prediction (Flyvbjerg et al., 2008; Flyvbjerg, 2007; Flyvbjerg et al., 2004; Flyvbjerg et al., 2003), when compared to e.g. travel times (Casello et al., 2014). In fact, the estimated travel times reductions are more likely to occur, but, on the other hand, capital and investment costs tend to increase substantially, either affected by endogenous factors, e.g. property acquisition costs for ROW; or exogenous factors, e.g. Baumol disease. In CBA, for example, increasing the discount rate may reflect the risk of future events that undermine future benefits accrued from the project. In MCDA, on the other hand, different weight profiles, reflecting points of view of multiple stakeholders, can be addressed in a sensitivity analysis.

2.8. The final choice

The final choice is the main outcome of the decision-making process. All steps and procedures described above are part of a comprehensive process that should lead the decision-maker to the best capital investment alternative, among a set of alternatives. However, this choice has often several weaknesses and there are multiple reasons for this, as highlighted in the literature. Decision-making sometimes fails for lack of technical robustness and excessive empiricism (Wright and Hook, 2007) with a high degree of political interests involved (Duarte and Ultramari, 2012; Gilbert, 2008). Even when the process is technically sound, the decision-maker ends up opting for a different, costly alternative, due to political interests or other reasons. There is a sort of "optimism bias" towards capital-intensive projects such as rail solutions (Hensher, 1999; Hodgson et al., 2013), as they might boost economic and land use development and attract car users. In some countries, this bias is embedded in the transit funding legislation (De Bruijn and Veeneman, 2009; Edwards and Mackett, 1996; Pickrell, 1992), and this can substantially limit the set of alternatives to rail or nothing (Banai, 2006; Prud'homme et al., 2011), hence penalizing what might be a substantial and important discussion regarding other possible and maybe cheaper solutions.

Other issues that might undermine the outcome are the considered variables and parameters. Current literature tends to highly value capital and operating costs, and travel time savings, followed by revenues, safety and environmental issues. There is a tendency towards favoring direct impacts which are somehow easy to quantify, forecast, appraise and monetize (Beukers et al., 2012), in detriment of more qualitative hard to monetize and to forecast indirect impacts. This is clearly the case of changes in land use patterns induced by transit investments.

Ignoring questions such as changes in accessibility, density, real estate prices and land uses (i.e. the actual activities occupying urban land) on transit decision-making is typically wrong (Douglas et al., 2013), as transit has marked and measurable impacts on land use (Damart and Roy, 2009; Eliasson, 2013; Lake and Ferreira, 2002; May et al., 2008; van Wee, 2012). Results from empirical studies about BRT and LRT impacts on land use significantly vary, but in general they present positive impacts on commercial and residential property prices as well as an increase in jobs, business clustering, mixed-use and densification (Knowles and Ferbrache, 2016; Deng and Nelson, 2010; Hass-Klau and Crampton, 2005; Stokenberga, 2014).

In fact, one of the reasons for ignoring land use issues is the difficulty of forecasting the impacts, since traditional transportation modeling software cannot accurately predict changes in land use, such as an increase (or decrease) in apartment rents near new transit infrastructures. To adequately deal with these issues, more sophisticated, expensive, time and data consuming (Martínez and Viegas, 2007) methods and models such as integrated LUT, hedonic and geographic weighted regression models are required. Moreover, strict focus on direct easy to monetize impacts, such as gains in travel time, leads to excluding relevant intangible impacts.

2.9. Conclusions and further research

Current capital investment decision-making on public transport systems incorporates a variety of aspects, techniques and models, to help choosing a transit technology from a set of alternatives under consideration. As presented in the Introduction of this chapter, a decision-making process can be structured in different ways and along various steps.

In what concerns the definition of the alternatives to be analyzed, this research focus on two main transit technologies that may be comparable and have some overlapping features – the BRT and the LRT. BRT emerged as a cost-effective alternative for rail-based systems. Back in the 70s, city planners in Curitiba had considered the implementation of an LRT, but the idea was aborted due to its high capital costs. With the urgent need to provide good public transport for a fast-growing city, the idea of improving the bus system by segregating its operation from the rest of the traffic emerged naturally. After almost 40 years, BRT systems have considerably evolved, integrating new features and solutions. In general, BRT and LRT are having a growing role in the future of cities. To cite just some recent and current undertakings: in Brazil, a new BRT in Belo Horizonte or LRTs in Santos, Rio de Janeiro and Cuiabá. During the last decade, China has opened or upgraded as much as 16 BRT systems, with various configurations and features. And in the US and Canada, planning or construction of LRT services is taking place in almost 40 different cities.

Regarding the decision parameters, the following aspects are typically considered: capital costs, operating costs, revenues / ridership, travel time, reliability, journey quality, comfort and crowding, safety, fitness and health and environment. Capital costs comprise all the money spent building the system (investments), while operating costs are the ongoing expenses, normally counted in an annual basis. Both tend to deviate from estimation, typically overrunning. In the absence of operating subsidies and government investment funds, those two costs should be covered by the revenue generated from operation. This is hardly the case since urban transit systems partially rely on public money. Nevertheless, revenue (or ridership), is naturally an important criterion to be considered in decision-making processes.

Reduction of travel time is an important direct benefit of a project. It represents the gains in journey times that can be assigned to a new or an improved transit system and is somewhat easy to be translated in monetary terms, and thus be incorporated in a CBA. In many countries, a Value of Travel Time Saving is defined. Even if it is normally seen as a disutility, recent research suggests the use of travel time for other purposes rather than just travelling, such as working, leisure and studying. The generalization and consolidation of driverless technologies should further foster this discussion as travel time will not necessarily be a disutility for passengers, after all. Issues related with reliability, journey quality, comfort and crowding might also affect travel time, hence they are not decision parameters, but effects to consider when assessing travel time gains.

Safety is another very important and well-established issue, with focus mainly on accidents and the on Value of Statistical Life (as considered by many countries). Using the VOSL and accident risk modeling, it is possible to estimate the monetary gains (or losses) of transit and transport capital investment projects. In another direction, recent studies in the impacts of transportation on medium to long-term health and fitness of populations show commuting by car is associated with obesity and other diseases, while walking, cycling and transit are, in general, associated to healthier lifestyles. Fitness and health benefits are not limited to individuals but rather to the whole society, since less trips by car and more trips by transit, walking and cycling will reduce air and noise pollution and accident risk. Incorporating fitness and health in traditional CBA is rather difficult, as such aspects are quite hard to monetize. MCDA is therefore an appropriate alternative to deal with these aspects.

Finally, the environment component comprises a variety of issues: noise, air pollution, visual impact, urban environment, and barrier effect. Environmental issues became common in transit decision-making recently, due to climate changes and growing concerns about developing more sustainable transportation systems. Some of these aspects are easy to monetize and fit well into a CBA, while other aspects require some sort of qualitative analysis, expert opinions, cost-effective analysis, or a MCDA approach.

When it comes to estimation and forecasting techniques, the four-step model stands out as a popular methodology for computing the impacts the investment alternatives have on selected variables, for various time periods. Shortly, the model is fed with population and activity data from the study area, and then the model steps of trip generation, trip distribution, mode choice and traffic assignment are performed, delivering values such as link volumes, volume to capacity ratios, transit ridership, load factors, travel times or number of congested links. However, the four-step model lacks travel behavior modeling and a connection between trips.

CBA and MCDA are two evaluation methodologies that can work separately or in an integrated way. While CBA monetizes all costs and benefits (producing Benefit Cost Ratios, Internal Rates of Return, or Net Present Values), MCDA uses weights, for the different criteria, to come up with a score for each project. Both methodologies have advantages and drawbacks and can work alone, or be combined in some way.

The next step is incorporating risk and uncertainty on the decision process. Sensitivity analysis aims to "doubt" the entire process and rethink assumptions, inputs, methods applied and utterly ask if we are solving or trying to answer the right problem. Utterly, sensitivity analysis tests the robustness of each alternative. Finally, the decision-making process delivers the final choice, i.e. the best investment alternative from a set of alternatives.

Current capital investment decision-making presents some shortcomings regarding the decision parameters and aspects, which are rather hard to quantify, estimate and evaluate, as it favors direct impacts that are somewhat easy to quantitate, forecast, appraise and monetize, in detriments of more qualitative hard to monetize and forecast indirect impacts. Changes in land use patterns induced by transit investment fit in the latter case. Ignoring land use issues is a strong assumption, as transit do have marked and measurable impacts on land use. One of the reasons for overlooking those issues relies on the difficulty of forecasting them. Another plausible reason for disregarding land use issues is the difficulty in evaluating them, since finding a monetary value, to input in a CBA, for e.g. gains in density or accessibility can be hard and unrealistic.

The next chapter will cover the issues raised here and will go on with the literature review, focusing on land use and transit decision-making.

3. LAND USE AND PUBLIC TRANSPORT DECISION-MAKING

- Introduction
- Accessibility
- Mixed-use, density and Transit Oriented Development
- Property prices and Value Capture mechanisms
- Forecasting land use changes
- Evaluating land use changes
- Conclusions and further research

3.1. Introduction

When zoning a territory, municipalities and public agencies normally partition it by the different types of use, hence determining the human activities such as living, working, shopping, leisure, education, or health. The distribution of human activities on space leads to the need of spatial interactions, or trips. This demand for trips implies the deployment of transport infrastructures, increasing local accessibility which, in the long-term, co-determines location decisions, resulting in changes on the land use system (Wegener and Fürst, 1999) – see Figure 13.

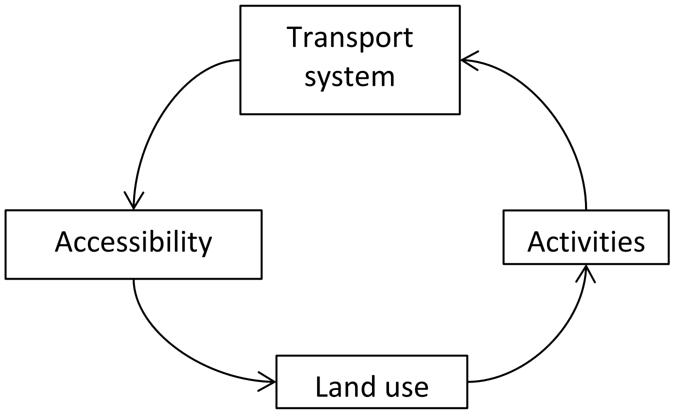

Figure 13 -Theoretical land use transport feedback cycle (Source: Wegener, 2004).

Land use is a broad term that encompasses the overall occupation of urban and rural lands by various human activities. A very simple categorization would be to consider residential and non-residential land uses, and a more detailed classification could cover: residential, agriculture, education, health, hotels, manufacturing, public entities, private offices, restaurants and retail (Martínez, 2010). Land use and transport interact, and shape each other since the first urban settlements.

Transit systems may have several direct and indirect impacts on land use. Some impacts may be quantified while others are better assessed qualitatively. Public transport systems can influence the value of surrounding properties and rents, affect population and job density, attract business and services, and therefore spur economic development[6]. The magnitude of impacts may significantly vary, but normally rail systems are considered to have larger effects on land use, when

[6] See Cervero and Kang (2011); Cervero and Kockelman (1997); Hass-Klau et al. (2004); Hess and Almeida (2007); Rodríguez and Targa (2004).

compared with road systems, especially because of the “sense of permanence” brought by the rail fixed infrastructure (Vuchic, 2002). However, some authors argue that road systems (requiring some ROW infrastructure), e.g. BRT, can have substantial positive impacts on land use, mainly when integrated land use and transport plans are implemented (Currie, 2006; Deng and Nelson, 2011), as it is the case of Transit Oriented Development (TOD) plans. The TOD concept is further discussed at 3.3.

In the previous chapter, most of the described decision parameters and aspects are reasonably easy to monetize and might fit in a CBA or be appraised using a MCDA or a qualitative approach. In this chapter, we consider aspects and parameters that are not so easy to monetize and hence demand a different evaluation method. They are accessibility, mixed-use, density and property prices. These parameters help us understand land use patterns and typically reflect the impacts caused by transit investment, mainly near stations. This chapter will discuss them on 3.2, 3.3 and 3.4, first by presenting their definition and presenting some ways for estimation and evaluation. On 3.5, forecasting methods linking land use and transport are presented, followed by 0 where the incorporation of land use issues on transit decision-making is overviewed, with focus on decision processes from the USA, Portugal and Brazil. Finally, 3.7 concludes the chapter and presents further research.

3.2. Accessibility

Accessibility can be defined as the ease of travel between places (Bertolini et al., 2005; Hull et al., 2012; Meyer and Miller, 2001). It differs from mobility as it focuses on potential of accessing numerous opportunities and not necessarily being able to travel long distances fast. The relation with transport and land use can be partially explained by accessibility (see Figure 13). Good public transport can greatly improve accessibility and mobility, especially for low-income groups. In general, good accessibility means more equity of access to opportunities, jobs and schools.

There are multiple ways of measuring accessibility and three fundamental elements are typically considered as independent parameters (Hull et al., 2012; Martínez, 2010): a defined “origin” (e.g. TAZ or stakeholder group); a set of relevant “destinations” or “opportunities” such as jobs, activities (e.g. hospital), or another TAZ; an *impedance* factor between each origin and each destination, that might be expressed as of a generalized cost:

$$A_{ij} = O_j f(C_{ij})$$

where A_{ij} is the accessibility from i to j; O_j stands for the opportunities at j; and $f(C_{ij})$ is the impedance function of the generalized cost for a trip from i to j.

Another, more intuitive and straightforward type of evaluation, is the *isochrone-based* accessibility measure, that represents the number of opportunities accessible from a given origin within a given amount of time (Accessibility Observatory, 2014; Dowd, 2015; Ingram, 1971; Hansen, 1959; Morris et al., 1979):

$$A_i = \sum_{j=1}^{N} O_j \, f(C_{ij})$$

$$f(C_{ij}) = \begin{cases} 1, & if\ C_{ij} < t \\ 0, & if\ C_{ij} \geq t \end{cases}$$

where A_i is the accessibility at i; O_j stands for the opportunities at j; $f(C_{ij})$ is the impedance function of the generalized cost (in this case, travel time) for a trip from i to j; and t is a travel time threshold, e.g. 30 minutes.

The isochrone-based approach delivers the count of opportunities that are reachable within the time threshold. Finally, a *utility-based* accessibility measure, that uses the *logsum* (i.e. the denominator of the logit model[7] on discrete choice models), as an accessibility measure (Ben-Akiva and Lerman, 1985; Geurs and van Wee, 2004), can be defined using the value of time.

The mentioned measures do not, however, forecast the increase of accessibility due to new transit supply. The outputs from traditional four-step models or integrated LUT models can be inputted on the referred measures, only then accessibility changes can be estimated.

The Accessibility Observatory at the University of Minnesota (Accessibility Observatory, 2014) estimates accessibility by car, transit and walking for American metropolitan areas. A representative transit accessibility map is depicted in Figure 14. In this example, Figure 14 shows the predominance of the Central Business District (CBD) (when compared to the suburbs). The CBD

[7] Multinomial logit models are employed in transport planning, in the four-step model and, more specifically, in the mode choice step. (See section 2.4 and Ortúzar and Willumsen (2011)).

concentrates most of the jobs and is well served by transit, thus ensuring smaller travel times and high accessibility levels.

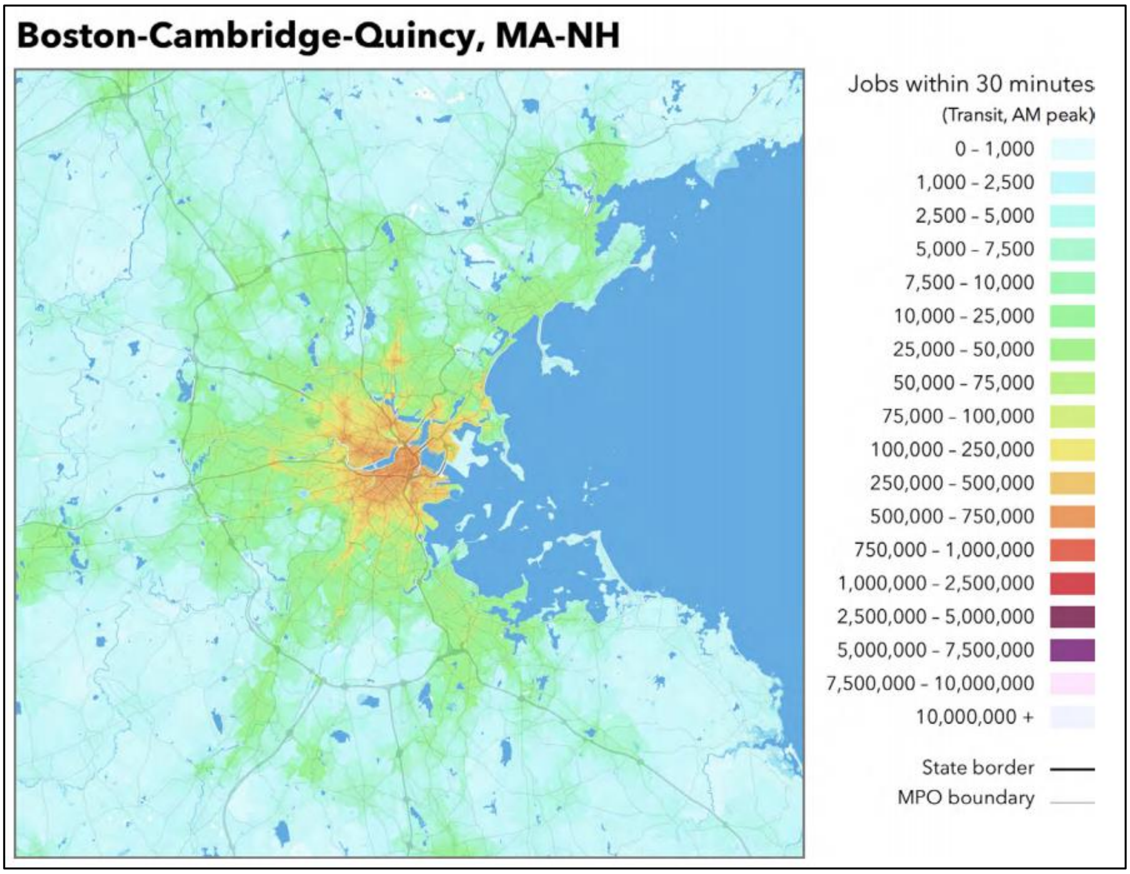

Figure 14 - Accessibility by transit at AM peak period (Source: Accessibility Observatory, 2014).

Accessibility on transport decision-making comes in different forms. The monetization of accessibility is uncommon and, in fact, few tests were tried with the *logsum* of the mode choice logit model (de Jong et al., 2005; Niemeier, 1997). On the other hand, non-monetized methods, e.g. MCDA, that appraise accessibility with its face value are quite common in terms of research (da Silva et al., 2008; Hull et al., 2012; Miranda and da Silva, 2012) and in legal planning procedures in the UK, Germany and Sweden (Gühnemann, 2013; Gühnemann et al., 2013; Hull et al., 2012; Eliasson, 2013). Figure 15 presents a decision process incorporating accessibility.

Finally, with integrated LUT models is possible to estimate the induced ridership accessibility changes might bring to transit systems (Figure 24) and ridership can be easily monetized for CBA.

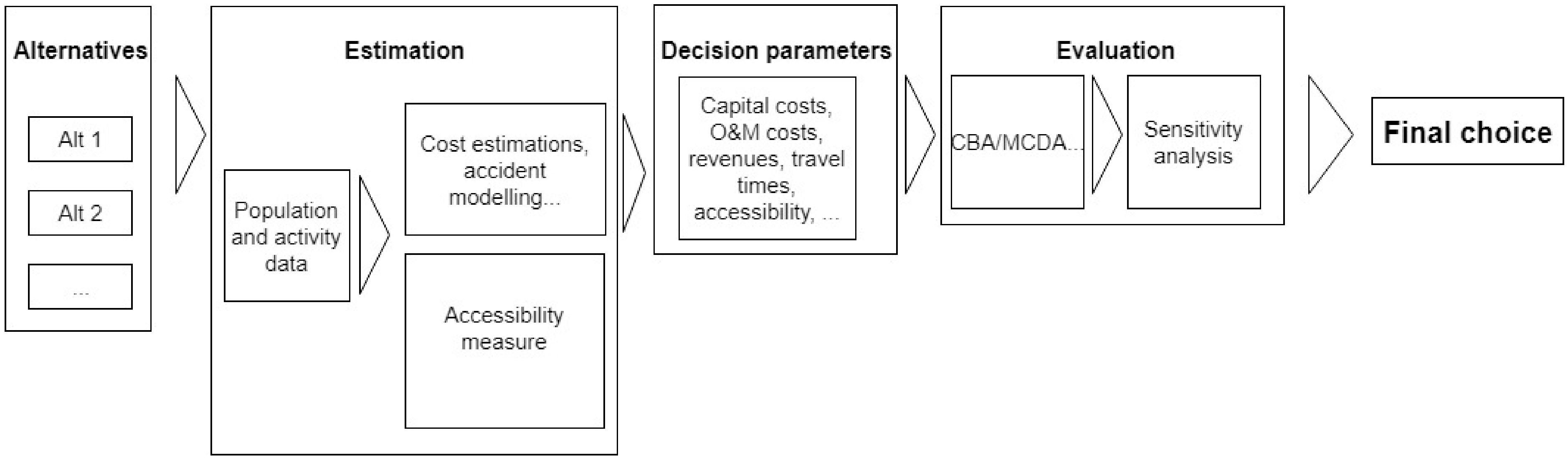

Figure 15 - A decision process incorporating accessibility

3.3. Mixed-use, density and Transit Oriented Development

There is a variety of land use factors that influence transit demand. Litman (2012a) summarizes regional accessibility, land use mix, and connectivity, as some important factors; and Cervero and Kockelman (1997) emphasize the 3Ds (density, diversity and design).

Density (meaning number of households, jobs or people per area) is, in fact, a crucial factor when designing transit systems (Figure 16). Density can substantially affect travel behavior, accessibility, transit demand and automobile use (Litman, 2012a). Kenworthy and Laube (1996) show a direct relationship between urban density and transit use. In very dense cities, such as Hong Kong and Singapore, the modal share of transit trips is substantially higher, when compared to cities such as Los Angeles and Houston (Petersen, 2004). With higher densities, transit ridership increases, making public transport financially more viable (Guerra and Cervero, 2010). Figure 17 depicts the relationship between petroleum consumption, a proxy for automobile use, and urban density.

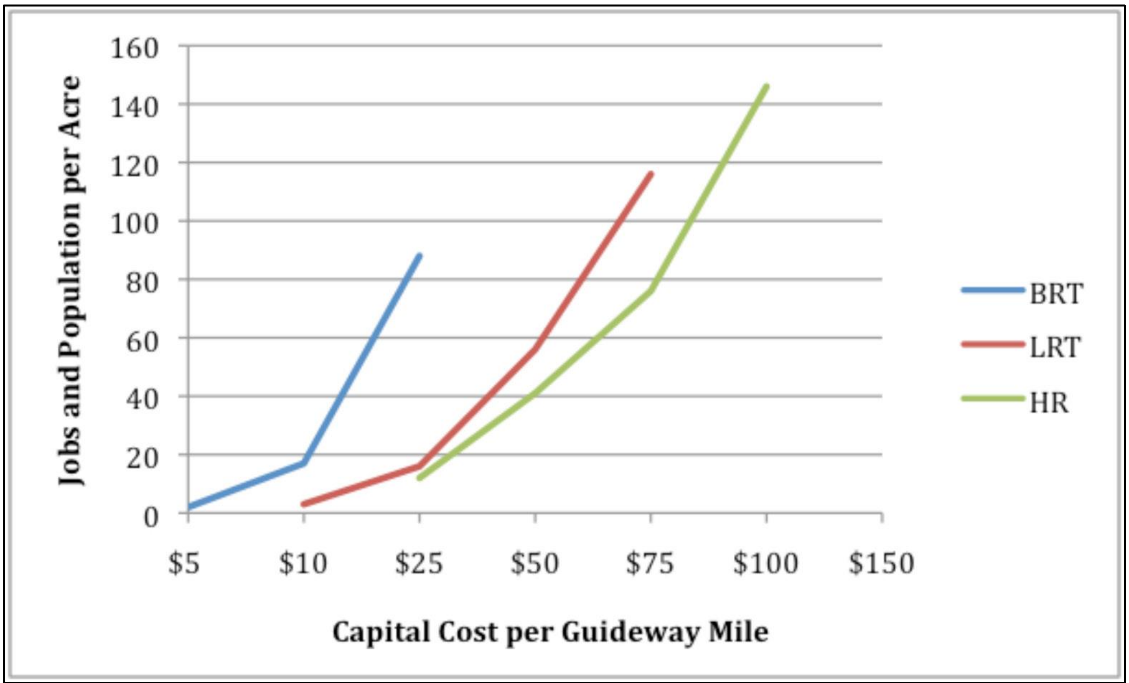

Figure 16 - Relationship between density and transit (Source: Guerra and Cervero 2010).

However, density alone can create dormitory suburbs and mono-functional employment centers, producing and attracting longer trips (Wegener and Fürst, 1999), and might therefore encourage automobile use.

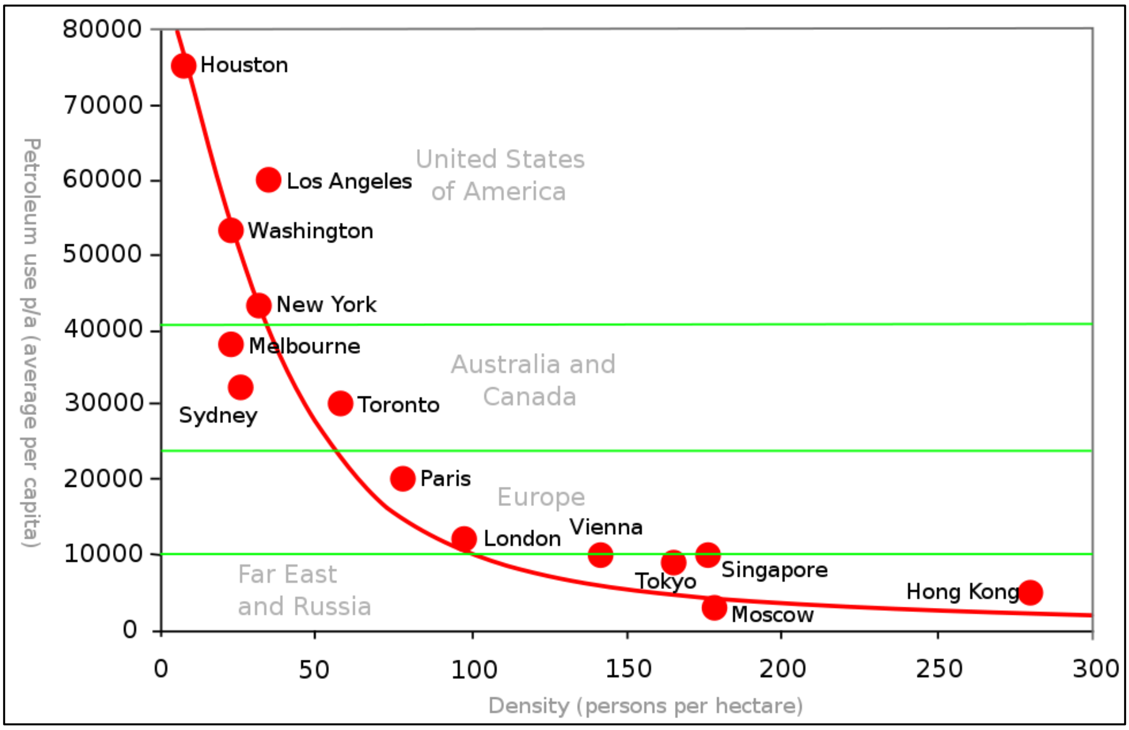

Figure 17 - Relationship between density and petroleum consumption (Source: Newman and Kenworthy, 1996; Wikipedia, 2012).

Another land use factor that can greatly influence transit use and reduce trips lengths is *mixed-use* (Cervero and Kockelman, 1997). Mixed-use or diversity is the location of different, but compatible, land uses close together. One very common mixed-use example is a building with commercial use such as restaurants on the ground floor, and residential use on the upper floors.

A transit station can be part of a mixed-use arrangement. Retail development can greatly benefit from costumers living and working near transit stations and from transit users transferring in a station. Vuchic (2007) states that, as early as the 1960s, LRT malls were already introduced in Western Europe and in the USA, increasing system ridership and access to activities in a pedestrian-friendly environment. The Skytrain in Bangkok, the TransMilenio in Bogotá, the MTR in Hong Kong, or London's Canary Wharf Business District (Wright and Hook, 2007) are some examples of successful integrated transport/retail plans. In those systems, the transit agency, predicting the future economic benefits the systems would bring, provides retail space inside or very close to the stations. Table 16 shows some empirical evidence about the impact of transit infrastructure on mixed-use and density[8].

Table 16 - Transit impacts on neighboring land use

City	Mode	Impact	References
Seoul	BRT	Conversion from single-family residences to higher density apartments and condominiums	Cervero and Kang, 2011
Seoul	BRT	54% increase in employment density	Kang, 2010
Bogota	BRT	Increase in population density	Bocarejo et al., 2013
Denver	LRT	Commercial and multi-family land uses grows more near the systems	Bhattacharjee and Goetz, 2016
Nantes	LRT	About 25% of all new offices were located along a light rail line	Hass-Klau et al., 2004
Mexico City	Metro	Residential density increased significantly more around stations	Guerra, 2014

Mixed-use can shorten shopping, leisure and school trips, that can be done by walking and cycling, thus diminishing car appeal and increasing sustainability. By increasing the mix of uses, origins and destinations are more efficiently distributed, hence diminishing trip loads on traditional suburb-to-CBD corridors and dispersing trips throughout the city.

A way of potentiating mixed-use and density changes is through integrated land use and transport plans (see Figure 13). In a hypothetical scenario, accessibility improvements triggered by transport would define land use patterns which would then define travel patterns and, therefore, transport demand. However, this cycle is unbalanced as land use has a higher influence on transport than the opposite. It is easier to change travel patterns than location patterns. Moreover, land use heavily depends on favorable local zoning regulations that might hinder the potential benefits of transit investments. Figure 18 depicts a "realistic" feedback cycle (Börjesson et al., 2014).

For a transit system to have a larger impact on land use, favorable zoning regulations must support transit investment. Such planning processes are highly appreciated by FTA's decision process (see 3.6.1), to understand how committed a municipality is to the projects. Figure 18 presents a feedback cycle with integrated land use and transport plans, the so-called TOD plans.

[8] For similar studies regarding the impacts of transit investment on land use please refer to Banister and Thurstain-Goodwin (2011); Debrezion et al. (2007), (2011); Deng and Nelson (2011); Hensher et al. (2012); Legaspi et al. (2015); Stokenberga (2014); Wirasinghe et al. (2013).

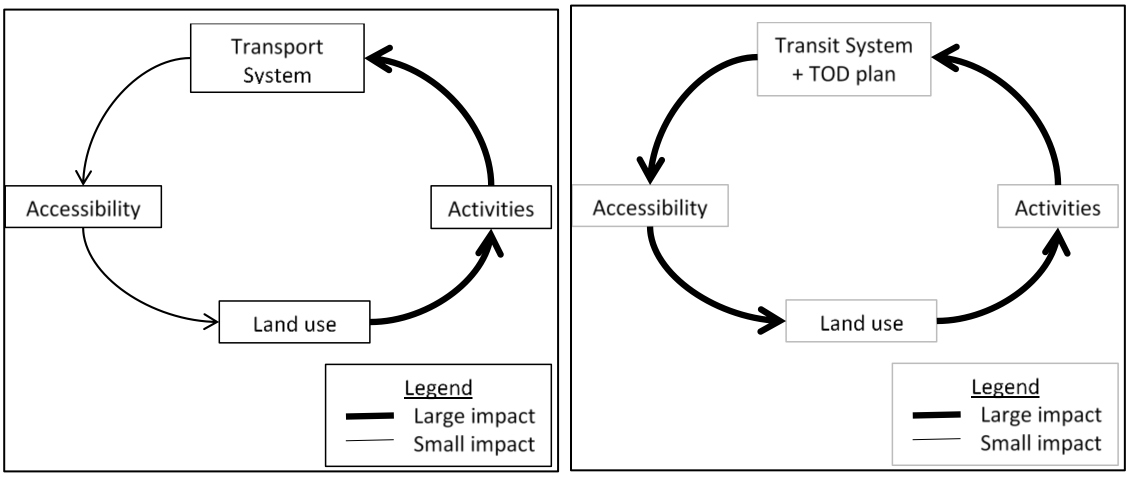

Figure 18 – "Realistic" feedback cycle (left) and feedback cycle with a TOD plan (right)

Transit Oriented Development (TOD) refers to residential and commercial developments designed to maximize access by transit and nonmotorized transportation (Litman, 2012b). A typical TOD has a rail or BRT station at its center, surrounded by a relatively mixed-use medium to high-density development, with progressively lower-density spreading outwards 1 to 1.5 kilometers (distances easily covered by foot or bicycle).

TOD emerged as a particular category of New Urbanism or Smart Growth movements (Martínez and Viegas, 2007), aiming to deliver more sustainable urban designs by trying to emulate the traditional small city of the late ninetieth century (Wegener and Fürst, 1999) around a transit station (see Figure 19).

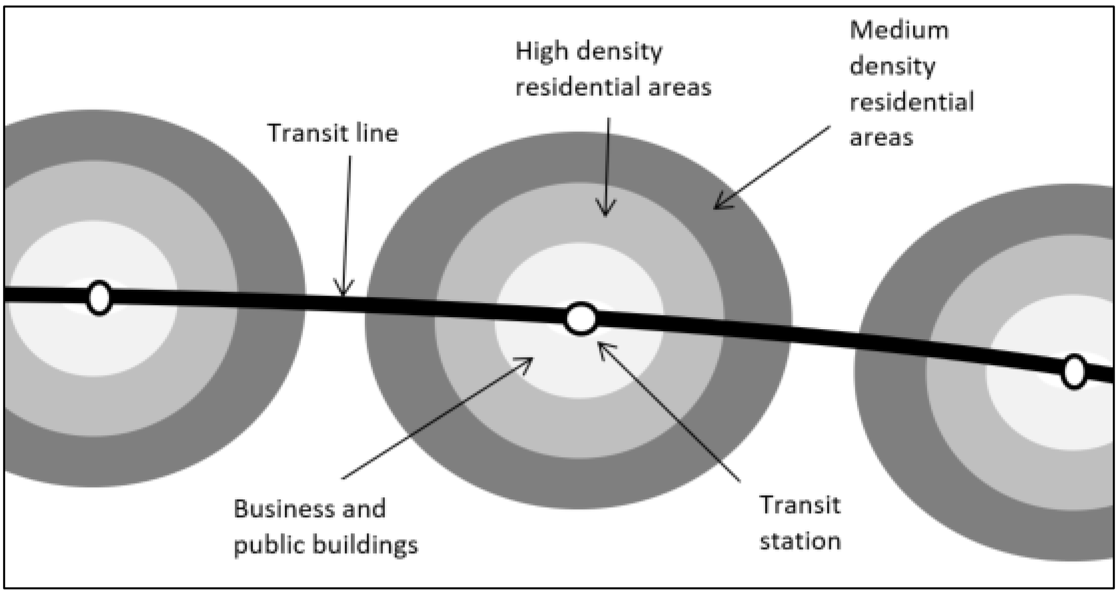

Figure 19 - A theoretical example of TOD

The main features of a good TOD plan are (Litman, 2012c; Meyer and Miller, 2001; Petersen, 2004):

- Density. As stated before, transit systems work better (have higher ridership) in higher densities. Density creates an economy of scale for transit, allowing more passengers per kilometer, with the same supply levels. Increase of household density or employment density nearby a transit station can bring more passengers (Petersen, 2004).
- Mixed-use. Mixing compatible land uses can improve the amenity of a neighborhood, and reduce travel times, costs and greenhouse gas emissions, by enabling more use of non-motorized transport modes, such as walking and cycling (Litman, 2012b). From the transport planning perspective, it is much more financially sustainable to have origins (home) and destinations (work) mixed throughout the city. This helps to avoid high demand peaks in one direction during the morning, and other high demand peaks in the opposite direction, in the evening, thus creating a multi-directional distribution of demand (Petersen, 2004), and making fleet and drivers management easier.
- Walking and cycling environment. Since most trips in TOD neighborhoods are short, providing safe walking and cycling conditions is crucial. Prioritizing pedestrians and cyclists over automobile (Meyer and Miller, 2001), but ensuring the access of emergence vehicles, are essential measures for a good TOD plan.
- Site design: Special concerns should exist on the design and implementation of buildings, public spaces and streets. Buildings facing the street and not isolated by walls or parking lots, with good pedestrian access and up to six stories (Petersen, 2004), having commercial use on the ground floor, office and residential use on the upper floors, and car access on the rear or an aside location are good features of a TOD.
- Traffic calming. Since pedestrians and cyclists have preference on a TOD scheme, slowing down the automobile traffic is essential for safety and community livability. A variety of measures can be combined: speed bumps, elevated crosswalks, different pavement surfaces and trees along the street are some widely used measures that can be implemented to reduce traffic speed and volume.
- Parking regulation. Efficient parking regulation can substantially decrease automobile use. Parking fees, shared parking, parking maximums and improved enforcement and control (Wright and Hook, 2007) are some measures to enhance parking organization.
- Freight regulation. Freight and delivery transport can be critical for a neighborhood, when poorly regulated. Light trucks and delivery vehicles should be only allowed in certain streets and at certain hours of the day, therefore preserving community livability and safety.

TOD can bring substantial benefits to all stakeholders involved. For the society, reducing oil dependence by less car usage can have positive impacts on the environment, on the economy and on the individual health. For the transit users, more destinations would be available near transit stations, with better walking and cycling conditions. And for transit operators, increased ridership, decreased costs and better image are the main benefits (Clean Air Institute, 2011; TRB, 2007; Wright and Hook, 2007). However, a TOD plan demands municipalities to change zoning laws and ordinances, near future transit stations. Changing zoning codes is a bureaucratic process that is neither easy nor fast, and requires a political consensus.

There are multiple ways to estimate mixed-use. Here, four different ways are presented: the Herfindahl-Hirschman index; the Diversity index; the Dissimilarity index; and the Entropy index (Cervero and Kockelman, 1997; Sung et al., 2014; Zahabi et al., 2011).

The Herfindahl-Hirschman index (HHI) is the sum of squares of land use percentages (i.e. activities). A higher HHI means a smaller level of land use mix. The highest value for the HHI is 10,000, and is reached when there is only one land use:

$$HHI = \sum_{i=1}^{N} P_i^2$$

where P_i is the share of land occupied by activity i; and N is the number of activities.

The Diversity index (DI) for two types of land uses, e.g. residential and non-residential, is calculated with the expression below. The mix of uses is higher if DI is close to 1:

$$DI = 1 - \left|\frac{P_i - P_j}{P_i + P_j}\right|$$

where P_i and P_j are the shares of land occupied by activities i and j.

The Dissimilarity index (DSI) is the proportion of dissimilar land uses among grid-cells within an area (Cervero and Kockelman, 1997):

$$DSI = \left\{ \left[\sum_j^k \sum_i^8 \left(\frac{X_i}{8}\right)\right] \Big/ k \right\}$$

where k is the number of actively developed grid-cells; X_i is 1 if neighboring grid-cell differs from grid-cell j, and 0 otherwise. Each grid-cell has 8 neighbors.

Finally, the Entropy index (EI) is the mean entropy for land uses among grid-cells, within a defined distance of each grid-cell inside a given area (Cervero and Kockelman, 1997; Martínez, 2010). EI goes from 0 (homogeneity, a single land use) to 1 (heterogeneity, land uses are evenly distributed):

$$EI = \sum_{i=1}^{k} \frac{P_i \ln(P_i)}{\ln(k)}$$

where P_i is the share of land use i; k is the number of land uses.

Different from mixed-use indices, density is a straightforward concept. Population density, i.e. population per area, and employment density, i.e. employment per area, are two common density metrics. As in the case of accessibility, the great challenge is not calculating mixed-use and density indices, but estimating changes in population, jobs and land uses, triggered by transit investments. Such forecasts can be done with integrated land use and transport models.

Mixed-use and density cannot be easily monetized to fit in a CBA analysis. However, with integrated land use and transport models, it is possible to estimate the induced ridership that mixed-use and density changes might bring to transit systems, with ridership being easily monetized for CBA (Figure 24). Börjesson et al. (2014) tested this hypothesis on a large-scale integrated LUT model for Stockholm, and evaluated six rail and road investments in the region. They found that induced demand by land use changes has a larger (but marginal) impact on rail than road investment projects. New rail or road infrastructures will not substantially increase local accessibility levels so that households and businesses are "convinced" to relocate, in a city with already a mature transport system as Stockholm. However, following a similar approach in a city-wide scale and not limited to station areas, the study developed by Shefer and Aviram (2005) estimates the future impact caused by Telavi's LRT project, in terms of the number of employees in the CBD and their potential contribution to the total annual production of the CBD. These benefits are an input to a CBA, leading to an increase in the BCR from 1.15 to 1.40. Alternatively, mixed-use and density might be simply evaluated with their face value in a MCDA or in another qualitative method, as it was done in the cases of Australia and New Zealand (Douglas and Brooker, 2013; Douglas et al., 2013).

Concerning TOD plans, instead of forecasting and evaluating land use changes, local municipal ordinances are redesigned to capitalize on transit accessibility and promote TOD. This approach basically assumes that we should not hamper developers with burdensome legislation preventing from building dense mixed-uses near transit (we should in fact promote it). In that way, the decision-maker knows, to a certain degree, that mixed-use and density changes will happen, even if he does not fully anticipate these changes. TOD plans can then be evaluated with a MCDA or another non-monetized methodology (see Figure 21).

3.4. Property prices and Value Capture mechanisms

With the improvement of local accessibility induced by transit, new developments might occur around transit stations, with an increase in property prices. Typically, after an announcement of future construction of transit infrastructures or the improvement of transit service, rents and property prices start slowly increasing. When the new facilities or services start opening, prices tend to stabilize, unless the system is expanded or improved again (Figure 20 depicts this pattern).

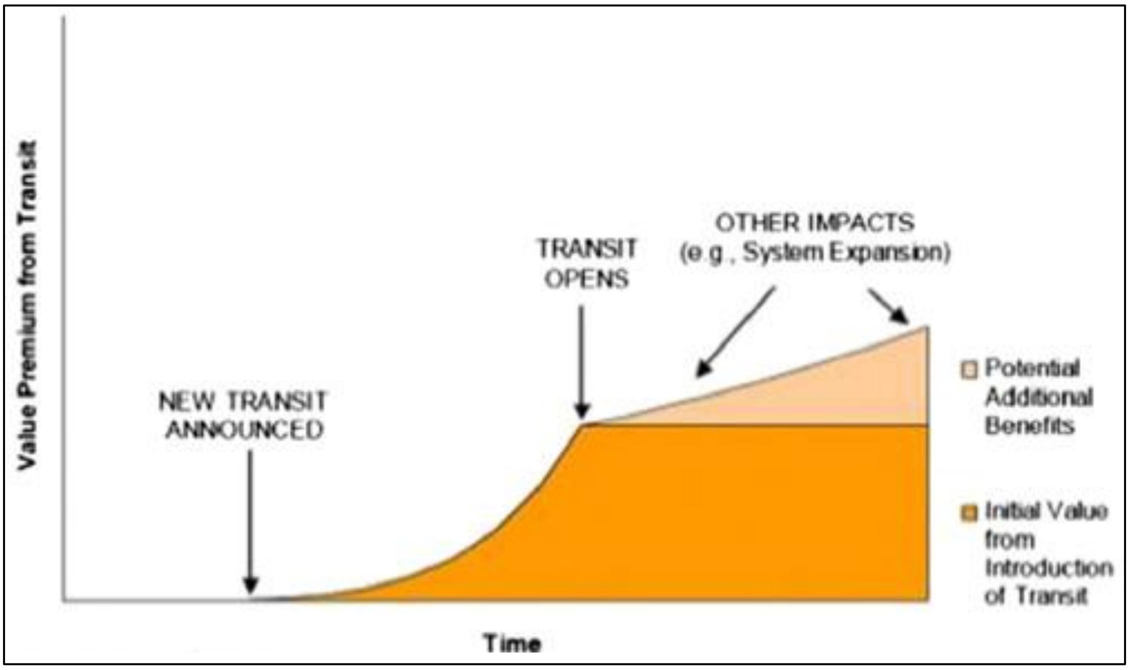

Figure 20 – The value premium from transit along time (Source: Knowles and Ferbrache, 2016).

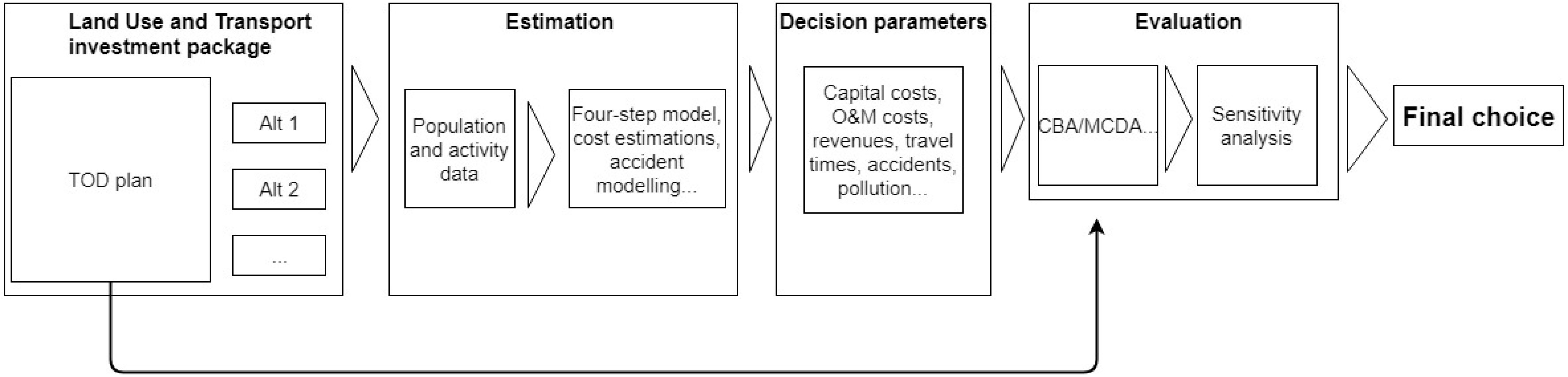

Figure 21 - A decision process incorporating TOD plans

When studying the impact of the BRT system in Seoul, Cervero and Kang (2011) concluded that land price premiums of up to 10% were observed on residences within 300 meters of BRT stops, and conversion from single to multi-family residences occurred fairly close to BRT stops. However when Jun (2012) studied the same system one year later, he concluded that residential rents did not considerably change because of the BRT, but instead non-residential activities, such as retail and offices, beneficiated the most from this transit system.

Another positive effect found by Perk and Catalá (2009) when analyzing the impact of BRT stations on the values of surrounding single-family homes in Pittsburgh, is that a property 300 meters away from a station is valued approximately US$ 10,000 less than a property 30 meters away from it. A similar result is found in Deng and Nelson (2010) and (2013) when studying Beijing Southern Axis BRT Line 1 - from 2004 to 2009, the average values of residential properties near a BRT station increased faster (annually 2.3% higher) than those not served by the BRT. The survey shows that the BRT system has a high profile within the local property market, being well considered by real estate agents and customers: the travel time savings provided by the BRT have made locations near a BRT station more desirable for development (Deng and Nelson, 2013).

Bocarejo et al. (2013) analyzed the impacts of Bogotá's TM, revealing that it had a positive effect on surrounding commercial property values and divergent effect on residential property values. Similarly, Perdomo Calvo et al. (2010) studied the TM impacts by focusing on selling prices of buildings between two homogeneous areas, one with BRT access and another without. The authors conclude that residential properties with easy access to the TM have an increase of 5.8% and 17% on their selling price. However, they recognize that the TM “brought” some retail, health and bureaucratic services and therefore the proximity of such services benefited the properties as well. Rodríguez and Mojica (2009) research the longitudinal (2001 and 2005) residential property values impacts caused by the TM extensions. The results show that, after the extension inauguration, properties in the intervention area had asking price increases between 13% and 14% higher than the properties in the control area, demonstrating the capability of the system to benefit from not just the land uses and properties in the proximity of new stations and corridors, but also from an indirect regional network effect.

One of the first studies about Bogota’s TM, performed by Rodríguez and Targa (2004), present a 2002 cross-sectional study comparing rent values between BRT and non-BRT served areas concluding that access to a BRT station is positively valued by the land market in Bogotá and should be related to higher property values, but closer proximity to the corridor should be related to lower property values. They concluded for Bogotá's TM that, after two years of operation, residential rent prices ascended between 6.8% and 9.3% for every five minutes walking time to BRT stations.

The research of Yan et al. (2012) aims to understand the impact of a new LRT system on single-family housing values in Charlotte, North Carolina, from 1997 to 2008. The results show that before the system operation, proximity to the corridor had a negative influence on home prices, likely due to the proximity to old industrial land use zones. After operation started, housing prices began to respond positively, showing greater temporal impact rather than spatial impact. These findings show that the presence of the system had greater influence in the city housing market than the proximity to the system.

Debrezion et al. (2011) conduct a similar research on Amsterdam, Rotterdam and Enschede (in the Netherlands), but improving the accessibility measurement. Instead of just using the distance to the railway station, they also consider an index of quality of railway services, provided at the station for two different models: one for the nearest railway station and another for the most frequently chosen railway station. They find that the most frequently chosen station influences more the prices of real estate than the nearest railway station.

Buffalo's LRT stations are studied by Hess and Almeida (2007). The study consists on assessing the impact on residential property values within half a mile of the stations. Results show that every foot closer to the station increases average values between US$ 0.99 and US$ 2.31. Therefore, a home located within one-quarter of a mile (400 meters) radius of a station can be valued as much as 2 to 5% more than the average home price in Buffalo. However, the authors also find that other independent parameters such as number of bedrooms, size and location are more influential than station proximity, similar to what Mulley (2013) found in Sydney, Australia.

Debrezion et al. (2007) do a meta-analysis of previous empirical research to obtain the percentage change in property value per distance from the station. They conclude that railway stations are expected to have a higher positive effect on commercial properties when compared to residential properties for short distances from the stations. Between various rail systems, commuter rail stations have a bigger impact on property value, mainly because of their higher passenger throughput and network coverage and fewer stations. Commercial properties tend to benefit more from station proximity than residential properties: where the price gap between the railway station area and the rest of the city is about 4.2% for the average residence, it is 16.4% for the average commercial property (Debrezion et al., 2007). The authors also point out the negative correlation between freeway exits accessibility and railway stations. When highway accessibility is not explicitly addressed, railway impacts on property values tend to be overestimated (Debrezion et al., 2007).

Hass-Klau et al. (2004) make an extensive study regarding the economic impacts of LRT investments. The research shows a house price appreciation up to 20% in Newcastle upon Tyne (UK) and down to none in Saarbrucken (Germany) with some depreciation in the beginning, because of noise. In Freiburg (Germany) office rents per square meter on the periphery were nearly 37% lower than at similar locations served by the system. In Hannover (Germany) offices near the light rail line could hardly be rented out at all. The research shows great desire from major employers to be near an LRT station.

The empirical studies present multiple outcomes, with most systems benefiting nearby residential and commercial properties, although with some uncertainty. Table 17 summarizes these findings[9]. There are multiple approaches for estimating changes in property prices triggered by transit investment, however three techniques stand out: Land Use and Transport integrated models; Hedonic Price models and Geographically Weighted Regression models. Each of these models have drawbacks and advantages that will be discussed in the next section.

From another point of view, we might say that the increase in property prices due to transit investment can help finance the transit system. To do that, value capture mechanisms must be available to create a stream of financial resources from beneficiaries to the transit agency or operator. Value capture aims to recover part of the benefits received by property owners or developers due to infrastructure improvements, and use them to fund such improvements (Levinson and Zhao, 2012; Martínez and Viegas, 2012; Smith and Gihring, 2006; Zhao et al., 2012). The proceeds from value capture mechanisms are considered on CBA as capital influx for typically paying capital costs (Ferreira, 2015). According to Martínez and Viegas (2012) value capture mechanisms can be divided in two main groups: property-related taxes, and development land

[9] For a thorough literature review regarding transit impact mainly on property prices refer to Knowles and Ferbrache (2016); Debrezion et al. (2011b), (2007); Deng and Nelson (2011); Stokenberga (2014); Wirasinghe et al. (2013).

charges. On the first group, property-related taxes (Land Value Taxation (LVT), Tax Incremental Financing (TIF) and Business Improvement Districts (BIDs)) are a possible approach. On the second group, development land charges (Betterment Levy, land leasing, Joint Development, and Air rights) represent important mechanisms to raise financial revenue from properties, to transit operators and regulators[10]. In Japan, Hong Kong and Singapore, many urban rail stations have some sort of *Joint Development* or *Land Leasing* arrangement, where the private sector can participate. Just to cite an example, Tokyu Corporation in Japan is one of the first companies to create master planned developments around its train stations. Real estate revenues are responsible of up to 33,5% (Calimente, 2012) of Tokyu's total revenues. Figure 22 presents a decision process incorporating value capture.

The use of value capture is not a common practice, as many cities lack such mechanisms, either because they are not properly regulated or they are even forbidden (Ferreira, 2015), or because the cities do not have the political power or community support to implement them. Moreover, some municipalities are not interested in an increase in prices and rents, and rather prefer avoiding what is called gentrification (Martínez, 2010; Munoz-Raskin, 2010). The prices can rise so much that previous tenants would not be able to pay the new rents, displacing low-income households farther away. This happened in Curitiba, as researched by Duarte and Ultramari (2012), where most of the BRT system users live in the sprawled low-income periphery, whilst high-income families live in expensive apartments along the BRT corridors and rely on private cars as main mean of transportation. This type of process can compromise community sustainability and equity.

Such concerns are incorporated in the Federal Transit Administration's decision process presented below, which prioritizes projects ensuring affordable housing along the corridor. Nonetheless, in the absence of value capture mechanisms, the possible expected impacts on property values can be qualitatively evaluated, as proposed by Banai (2006) and (2010).

[10] To understand better how they behave see e.g. Martínez and Viegas (2012); Smith and Gihring (2006); Zhao et al. (2012) provide resourceful insights about them.

Table 17 - Transit impacts on neighboring property prices

City	Mode	Type	Findings	References
Seoul	BRT	Residential	Prices up to 10%	Cervero and Kang, 2011
Seoul	BRT	Non-residential	Prices up to 25%	Cervero and Kang, 2011
Pittsburgh	BRT	Residential	A property 300 meters away from a station is valued approximately US$ 10,000 less than a property 30 meters away from it	Perk and Catalá, 2009
Beijing	BRT	Residential	The average values of residential properties near a BRT station increased faster (annually 2.3% higher) than those not served by the BRT	Deng and Nelson, 2010
Bogotá	BRT	Residential	Prices up between 5.8% and 17%	Perdomo Calvo et al., 2010
Bogotá	BRT	Residential	Rental prices up between 6.8% and 9.3%	Rodríguez and Targa, 2004
Charlotte	LRT	Residential	The presence of the system had greater influence in the city housing market than the proximity to the system.	Yan et al., 2012
Amsterdam, Rotterdam and Enschede	LRT	Residential	It is possible for a residential property value to react more to a farther away but better served railway station than to a closer one but not as well served	Debrezion et al., 2011
Buffalo	LRT	Residential	Values up between 2% and 5%	Hess and Almeida, 2007
Various locations	LRT	Residential and Non-residential	Where the price gap between the railway station area and the rest of the city is about 4.2% for the average residence, it is 16.4% for the average commercial property	Debrezion et al., 2007
Newcastle upon Tyne	LRT	Residential	Values up to 20%	Hass-Klau et al., 2004
Saarbrucken	LRT	Residential	No change	Hass-Klau et al., 2004
Freiburg	LRT	Non-residential	Office rents per square meter on the periphery were nearly 37% lower than at similar locations served by the system	Hass-Klau et al., 2004
Hannover	LRT	Non-residential	Offices near the light rail line could hardly be rented out at all	Hass-Klau et al., 2004

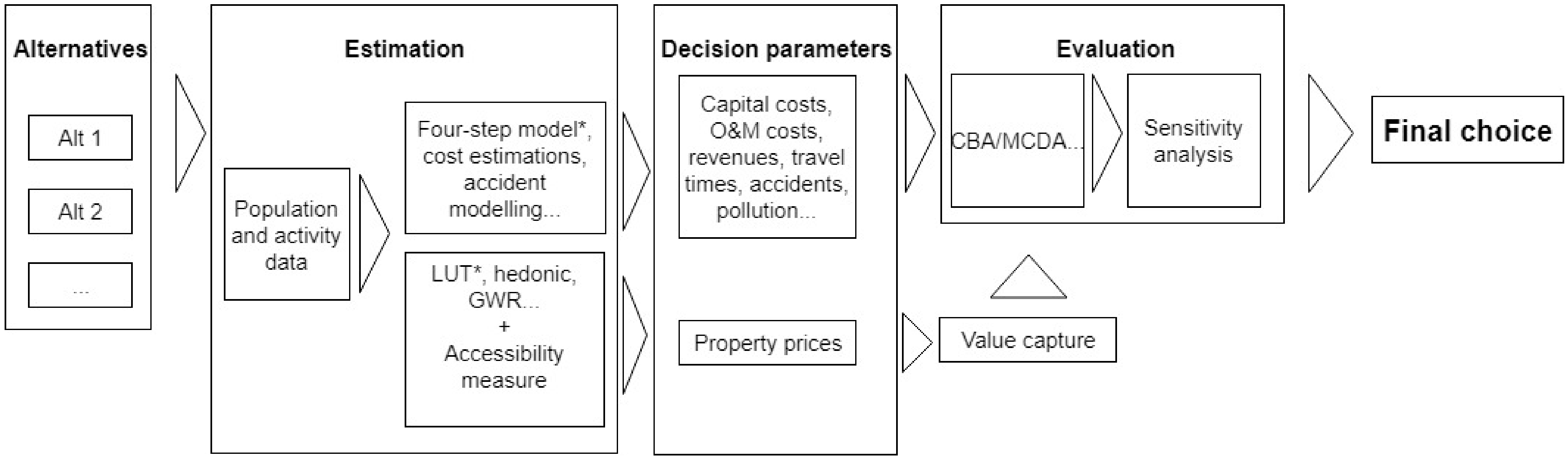

Figure 22 - A decision process incorporating value capture.
** LUT can replace the four-step model as transport modeling tool.*

3.5. Forecasting land use changes

3.5.1. Land use and transport models

The first Land use transport (LUT) models (Lowry (1964) cited by Meyer and Miller (2001)) tried to simulate and forecast possible changes in land use or transport caused by policy options, new urban developments, new transport infrastructure or transit services. The main difference between LUT models and regular four-step transport models is that LUT models forecast land use changes and link them with transport modeling (Wegener, 2004), by creating a derived demand of trips from the location choices of various activities. The transport modeling part can also be made endogenously (within the LUT model structure) or exogenously (by inputting the land use data on a transport model).

These different models can be partially or totally integrated. In the partially integrated approach, land use changes affect transport outcomes or the other way, while in the totally integrated models, land use changes affect transport outcomes which will feedback land use, completing the land use and transport feedback cycle (Figure 13). Figure 23 presents a general framework of LUT models (Southworth, 1995).

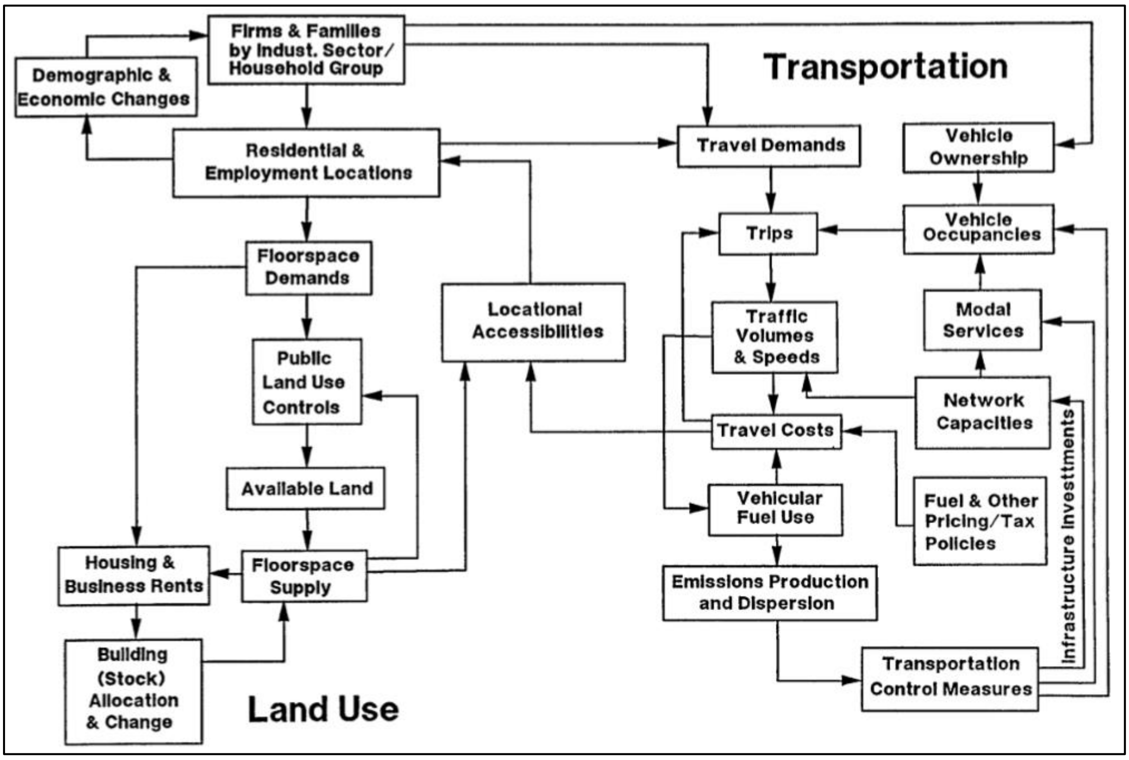

Figure 23 – General framework of LUT models (Source: Southworth, 1995).

The evolution of LUT models can be divided in four generations (Meyer and Miller, 2001; Santos, 2013; Wegener, 2004). The first generation comprises heuristic/Lowry/Lowry-type models developed during the 1960s and early 1970s. The second group emerged in the 1970s when simulation models appeared, with NBER and CAM models as references. Operational models are the third generation, which began in the 1980s. Finally, Microsimulation models are the current generation.

During the first of these generations, there were the first attempts to model complex urban dynamics using linear programming, simultaneous equation systems and simulation models (Meyer and Miller, 2001). In particular, the Lowry model analyzed employment and residential location and their distribution on land, dividing employment in two types, basic and retail. The second generation consisted of large-scale, aggregate mainframe-based models that stimulated the changes in urban activity throughout the years (Meyer and Miller, 2001). Simulation models included a more explicit behavioral (micro-economic) theoretical foundation of the relations between building demand and supply, real estate pricing, different households and decision-makers (Santos, 2013). The NBER and CAM models are references of this period. The third and most productive generation include aggregate models based on macro-economic theory and location theory (Vön Thunen (1826) cited by Martínez (2012)). They are more concerned about the flows of land use and transportation parameters (Some examples are Meplan, Mussa and Tranus).

Currently, the focus is on microsimulation models. These models are in general more disaggregated and focused on an agent or event, a household, an employer / employee, driver, passenger, as a decision-maker (Martínez, 2012), and are typically based on project development catalogs, hedonic and discrete choice modeling, rule based and game theory. Some well-known examples are ALBATROSS, ILUTE and UrbanSim (Wegener, 2004). Wegener and Fürst (1999) present a list of land use and transportation policies simulated in modeling studies (see Table 18).

LUT models are very sophisticated, data intensive, expensive to build and to keep updated (Santos, 2013). Other modeling approaches such as Hedonic Models and Geographically Weighted Regression can estimate changes triggered by transport investment on land use factors such as property prices (Martínez and Viegas, 2007).

Table 18 - Policy impacts on modeling studies (Source: Wegener and Fürst, 1999).

Policy area	**Example**	**Model impact**
Land use	Peripheral Shopping center	Strong decentralization effect on retail employment and population. Negative economic impact on city center. Car use increases.
	Centralization of population as employment	Only slightly reduced trip distances, share of car trips and energy use.
Transport	Outer ring road construction	Further decentralization of population. Less congestion in the city center, positive effect on downtown retail. Travel distances increase, mainly by car.
	Higher fuel taxes	Strong reduction of number and length of car trips and significant shift to public transport. Retardation of decentralization of employment and population
	Free public transport	Less decentralization of employment and more of population. Benefits for inner-city retail. Strong increase in distance travelled but little reduction in car trips.

A decision process incorporating a LUT model is depicted in Figure 24. The LUT model updates baseline population and activity data, thus considering an induced demand until a certain moment, when evaluation is performed.

3.5.2. Hedonic models

Most hedonic models are based on Rosen (1974), where each property consists of an inseparable bundle of homogeneous attributes that differ in values and characteristics (Targa and Rodríguez, 2003). The price of the property is then defined as a function of the values of each attribute in the bundle, such as the following way (Hess and Almeida, 2007):

$$P = f(Pr, H, L, N)$$

where P is the assessed property value in dollars; Pr is a vector of parameters that measure the proximity of properties to light rail stations; H is a vector of parameters that describe housing characteristics; L is a vector of parameters that describe locational amenities; and N is a vector of parameters that describe neighborhood characteristics.

The independent parameters are the attributes that, when combined, form the price of the property and are normally related to internal property features, e.g. number of bedrooms and garages; neighborhood amenities, e.g. a mixed-use zone, local services; and locational attributes such as accessibility to transportation systems (Targa and Rodríguez, 2003). The internal property attributes proposed by Martínez and Viegas (2012) for a hedonic model for Lisbon were

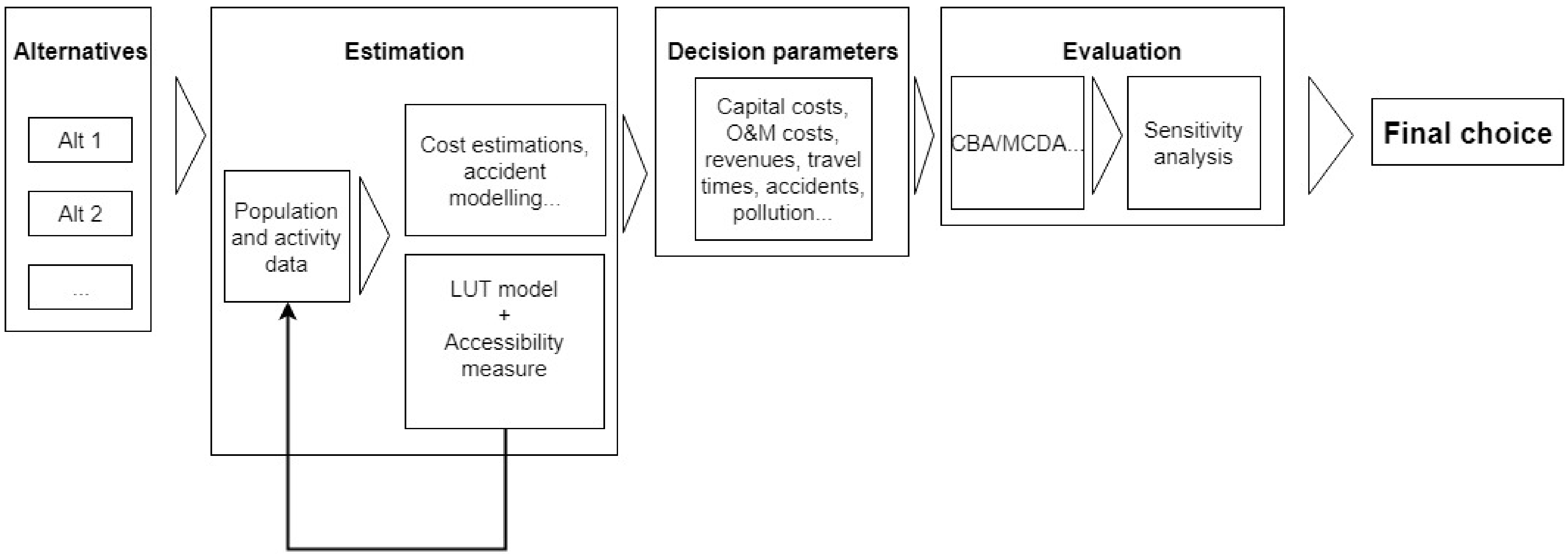

Figure 24 - A decision process incorporating a LUT model

the number of bedrooms, area, type of property (i.e. a house or apartment), age of the property, floor number, and garages. Moreover, an education index, an entropy index and five different accessibility measures were proposed as external attributes.

All these attributes come from different databases and some of them must be estimated beforehand, such as accessibility indicators. Such detailing and sophistication leads to case-specific and data-consuming models that need to be estimated for each city and time[11].

3.5.3. Other forecasting methods

For estimating changes in property prices, another technique similar to the hedonic model is the Geographically Weighted Regression (GWR) (Fotheringham et al., 1998). GWR defines a bundle of internal and external attributes of a property, to estimate its price, taking into account spatial dependency in the estimation process (Mulley, 2013). GWR is not as broadly used as hedonic models mainly because of the reduced number of software applications offering this tool (Martínez, 2010). As with hedonic models and LUT, GWR needs large datasets of disaggregate data, to properly estimate the relations between transport and land use.

Other techniques for estimating land use changes derived from transport (and vice-versa) can range from simple comparison methods (Cervero and Landis, 1993; Pasha, 1995), expert opinions, GIS tools (Bocarejo et al., 2013; Pacheco-Raguz, 2010; Perdomo Calvo et al., 2010), agent-based models (Shen et al., 2014b), spatial discrete choice models (Shen et al., 2014a) to complex structural equation models (Bagley and Mokhtarian, 2002; Eboli et al., 2012; van Acker et al., 2007).

3.6. Evaluating land use changes

Contrary to what happens with more traditional benefits such as travel time savings, changes in land use are seldom considered in decision-making (Börjesson et al., 2014; Camargo Pérez et al., 2015; MacKie and Worsley, 2013). This happens mainly because they are hard to monetize, they are often considered as a value transfer instead of a value creation, and they are too complex to

[11] For further detail on hedonic models, please refer to Billings (2011); Hess and Almeida (2007); Martínez (2010); Yan et al. (2012).

be assessed by traditional transport modeling software. Nevertheless, these changes might strongly influence the decision process. The reduction of travel times is still considered the main criterion to choose a solution (Metz, 2008), normally followed by safety related issues, capital and operating costs and pollution. Land use changes are sometimes evaluated in a qualitative way or not considered at all. Some authors (Damart and Roy, 2009; MacKie, 2010; Shefer and Aviram, 2005; TRB, 2011) question accounting approaches for economic or land use benefits, as this could lead to double counting, mainly because part of the increase on property values may be due to lower transportation costs (e.g. travel time savings). Other authors believe changes in land use might be small and neglectable when supporting zoning laws (e.g. TOD plans) are absent (Börjesson et al., 2014; Damart and Roy, 2009; Higgins and Kanaroglou, 2016).

This section presents a detailed review of three official (i.e. carried out by national funding agencies) decision processes for transit capital funding: The Federal Transit Administration (USA); the Growth Acceleration Program (Brazil); and Metro do Porto (Portugal). We analyze here how these entities incorporate land use issues, when selecting a project for funding, among a set of potential projects.

3.6.1. Federal Transit Administration

The current analysis is based on 5309 Capital Investments Grants, in the framework of FTA's primary grant program for funding major transit investments such as heavy rail (HRT), commuter rail, LRT, streetcars, and BRT (FTA, 2015). The projects must fit one of three categories: Small Starts, New Starts, or Core Capacity. The funding recommendations for the fiscal year of 2017 (FTA, 2016a) proposes 63 projects ranging from streetcar to commuter Rail. Table 19 presents a brief overview on these projects.

All three categories follow a set of evaluation and rating criteria defined under the *"Moving Ahead for Progress in the 21st Century Act"* (MAP-21), enacted on July 6, 2012. The rating is based on two major criteria (i.e. summary ratings): project justification and local financial commitment (each one weighting half of the overall rating). Figure 25 briefly describes the rating processes.

Project sponsors (e.g. transit agency) must submit to FTA estimations about land use and economic development, for evaluation and rating of the project (land use and economic development effects summary templates and supporting documentation, and a table of quantitative data on land use characteristics). Core capacity projects do not need to comply with the land use criterion but rather with a "Capacity Needs" criterion.

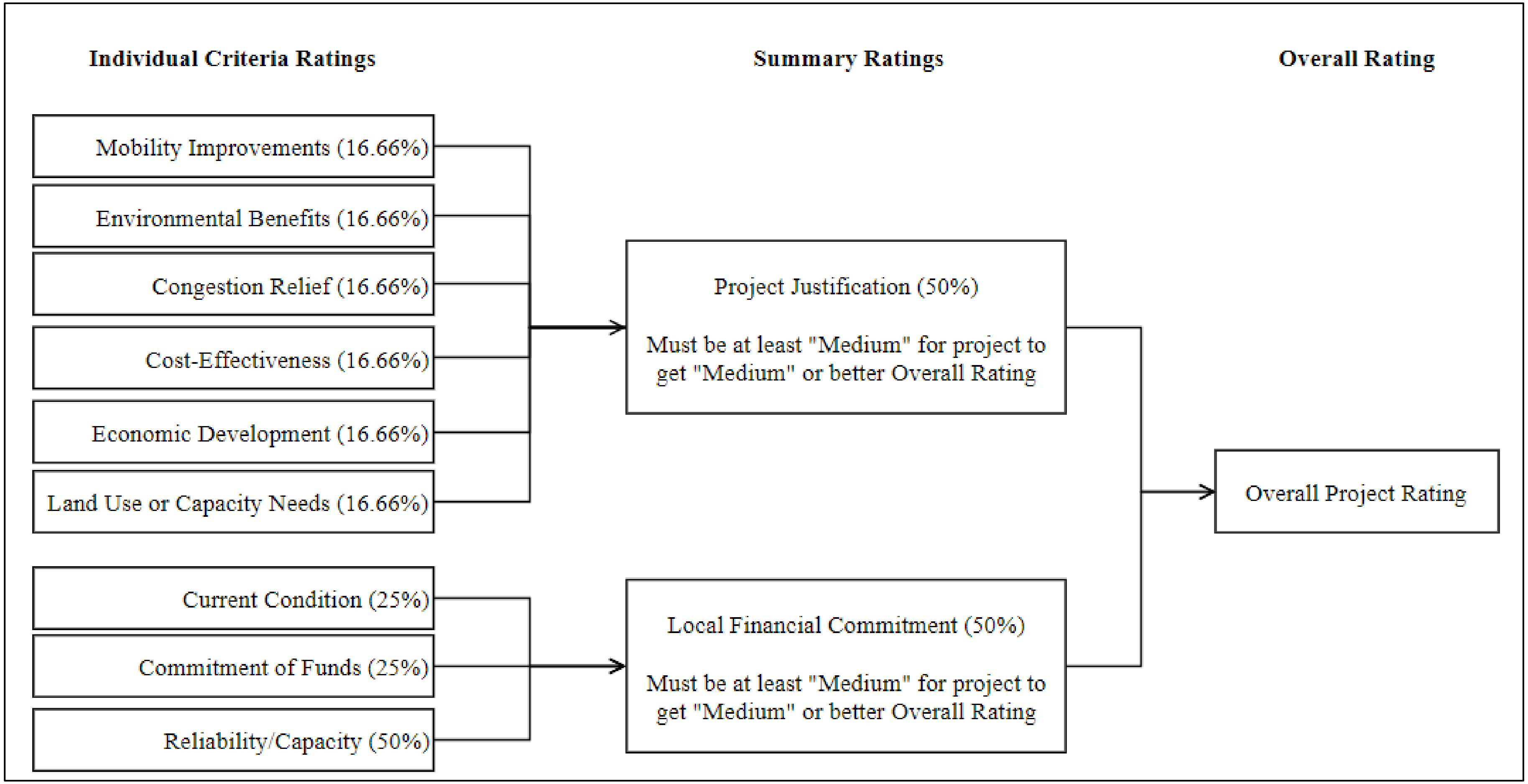

Figure 25 - FTA's rating process (Source: FTA, 2015).

Table 19 - 2017 Funding Recommendations

Mode	**Capital cost per km (M US$)**	**Annual operating cost per km (M US$)**	**Land use rating**	**Economic development rating**
BRT	8.7 (21)	0.95 (11)	Medium (11)	Medium (11)
Commuter rail	18.8 (7)	0.70 (4)	Medium-Low (2)	Medium-Low (2)
HRT	285.8 (5)	0.43 (2)	Medium-High (1)	Medium-High (1)
LRT	156.1 (16)	1.01 (9)	Medium (7)	Medium-High (7)
Streetcar	40.2 (7)	1.19 (7)	Medium (7)	Medium-High (7)

Note: Estimated average costs and ratings of transit projects recommended for funding by FTA for Fiscal Year 2017. The figures in brackets are the projects with available information.

3.6.1.1. The land use criterion

FTA asks for existing land use characteristics within a half-mile radius of each proposed station and CBD. The items analyzed are:

- existing corridor and station area development;
- existing corridor and station area development character;
- existing station area pedestrian facilities, including access for persons with disabilities;
- existing corridor and station area parking supply; and
- proportion of existing legally binding affordability restricted housing in the corridor compared to the proportion of legally binding affordability restricted housing in the counties in which the project travels.

The rating consists on a five point-scale going from Low, Medium-low, Medium, Medium-high to High. Albeit ratings are based on quantitative measures, qualitative aspects such as the quality of the pedestrian environment affect the final rating.

For a project to obtain a high rating, the current levels of population and employment within half-mile from stations must be enough to justify a major transit investment, and most station areas must be pedestrian-friendly and fully accessible. The share of affordable housing in the corridor compared to the counties the project runs through must also be high.

To evaluate the first item ("existing corridor and station area development"), we need to start by estimating the total employment along the entire line on which a no-transfer ride from the proposed stations can be reached, and the average population density (see Table 20). The second and third items ("existing station area development character" and "existing station area pedestrian facilities") are measured qualitatively and to justify "medium-high" or "high" ratings, the urban environment (i.e. character) should encourage transit use by having a more human oriented scale (instead of a car oriented one), providing amenities such as street furniture and trees, narrow streets, absence of surface parking lots, short building setbacks, and building entrances facing the street along with good and continuous sidewalks. With these features, a fine-grained mix of uses with retail, office and residential uses neighboring each other, allowing people to run errands and make short walking or transit trips are highly appreciated. To come up with the ratings on qualitative items, FTA reviews ground level/aerial photographs, satellite imagery, station area maps, as well as the narrative description provided by the project sponsor.

The fourth item ("existing corridor and station area parking supply") asks for quantitative data about CBD parking supply, CBD typical parking cost per day, and CBD parking spaces per employee, as depicted on Table 20. Proposed station areas parking supply may be assessed qualitatively through aerial photographs and maps.

Finally, the fifth and last item in the land use criterion ("existing legally binding affordability restricted housing"), is a quantitative measure of the proportion of affordable housing on station areas: the percentage of existing housing units in transit station areas that are "legally binding affordability restricted" units is compared to the percentage of existing housing units in the county or counties through which the transit project travels that are "legally binding affordability restricted" units. To calculate the proportion, the project sponsor must collect data on housing units that have and have not legally binding affordability restrictions for the stations areas as well as for the counties where the project stands.

A ratio between the percentage of existing units in the proposed transit corridor (that are legally binding affordability restricted housing) and the percentage of existing units in the county(ies) (that are legally binding affordability restricted housing) is rated as depicted on Table 20.

3.6.1.2. <u>The economic development effects criterion</u>

Alongside with the *land use* criterion, the economic development effects criterion also cares about land use issues. However, this criterion is concerned with future developments on the vicinity of the corridor and at a regional scale, while the land use criterion focuses on existing conditions along the corridor, and tries to measure how much "transit-friendly" are the city and the area of the project.

Table 20 - Land use ratings

Rating	Station Area Development		Parking Supply		Legally Binding Affordability Restricted Housing
	Employees served by system	Average population density (persons per square mile)	CBD typical cost per day	CBD spaces per employee	
High (5)	> 220,000	> 15,000	> US$ 16	< 0.2	Ratio > 2.50
Medium-High (4)	140,000 - 219,999	9,600 -15,000	US$ 12 - 16	0.2 – 0.3	2.25 < Ratio < 2.49
Medium (3)	70,000 - 139,999	5,760 - 9,599	US$ 8 - 12	0.3 – 0.4	1.50 < Ratio < 2.24
Low-Medium (2)	40,000 – 69,999	2,561 - 5,759	US$ 4 - 8	0.4 – 0.5	1.10 < Ratio < 1.49
Low (1)	< 40,000	< 2,560	< US$ 4	> 0.5	Ratio < 1.10

This criterion tries to measure how the various local transport and planning agencies are committed with such important federal-backed investment by evaluating transit-supportive plans and zoning ordinances which might foment TODs. It is based on ratings for 3 sub factors:

1. transit-supportive plans and policies;
2. performance and impacts of policies; and
3. tools to maintain or increase the share of affordable housing.

Sub factor 1 above covers growth management (just to New Starts), transit-supportive corridor policies, supportive zoning regulations near transit stations and tools to implement such policies. Performance of policies and potential impacts of transit investment on regional land use are covered by sub factor 2. To evaluate sub factor 3, FTA asks for corridor-specific affordable housing needs and supply, as well as plans, policies, financial tools and strategies to preserve and increase affordable housing in the region and/or in the corridor.

The quantitative indicators in this criterion rate the level of local commitment in promoting transit-supportive construction in station areas. In Table 21, with increasing commercial or residential density the project rating increases likewise. CBD commercial floor area ratios (FAR) greater than 10, and residential dwelling units (DU) per acre greater than 25, get the rating “High”. FAR smaller than 4, and DU per acre smaller than 5, get the rating “Low”.

On the parking policy, FTA rates as “High” projects with smaller than 1 and 1,5 spaces per 1.000 square feet in the CBD and other areas, respectively. The rating “Low” is for projects with greater than 3,25 and 3,75 spaces per 1.000 square feet in the CBD and other areas, respectively.

Qualitative evaluations are much more complex and detailed, requiring a thorough analysis on the land use plans and policies (not just around stations but around stablished activity centers throughout the area). Zoning ordinances favoring increased density and mixed-use around stations are highly rated, along with parking and traffic mitigation policies, and community engagement in the process.

Beyond demanding plans and policies, FTA also asks for performance indicators by requesting demonstrated cases of development affected by transit-supportive policies and station area development proposals and status. The potential of the investment to boost regional development is appraised as well. The affordable housing sub factor is of major concern of FTA. Tools to maintain or increase the share of affordable housing are rated highly by FTA standards. As a project progresses, local agencies should develop and adapt the required regulatory changes and incentives necessary to promote transit-supportive development patterns and affordable housing policies, along the transit corridor and in station areas (FTA, 2015).

Table 21 - Economic development effects ratings

Rating	**Station area development**			**Parking supply**	
	CBD commercial FAR	**Other commercial FAR**	**Residential DU per acre**	**CBD spaces per 1.000 square feet**	**Other spaces per 1.000 square feet**
High (5)	> 10.0	> 2.5	> 25	< 1	< 1.5
Medium-High (4)	8.0 – 10.0	1.75 – 2.5	15 - 25	1 – 1.75	1.5 – 2.25
Medium (3)	6.0 – 8.0	1.0 – 1.75	10 - 15	1.75 – 2.5	2.25 – 3.0
Low-Medium (2)	4.0 – 6.0	0.5 – 1.0	5 - 10	2.5 – 3.25	3.0 – 3.75
Low (1)	< 4.0	< 0.5	< 5	> 3.25	> 3.75

3.6.2. Growth acceleration program

In January 2007, the Brazilian government approved a 4-year infrastructure investment plan called *PAC – Programa de Aceleração do Crescimento* (Growth Acceleration Program). This program was further extended for 4 more years in 2011 and again in 2015 (Ministério do Planejamento, 2016). Most of the projects were for major metropolitan areas, 2014 World Cup venues and the Rio de Janeiro 2016 Olympics venue. Table 22 presents the main projects under construction or already operating as of 31 December 2015.

Table 22 - PAC projects

Transit system*	Estimated capital cost (2015 Billion US$)
BRT	1.6
Commuter rail	0.6
LRT	1.1
HRT	10
Monorail	1.8
Total	15.1

** Either new lines or extensions*

The decision criteria adopted by the Brazilian Government were stablished on an ordinance in February 2011 (Ministério das Cidades, 2011). This ordinance gave a chance to launch urban mobility projects that had not been chosen for funding by FIFA World Cup committee (under the first PAC program), but were nonetheless considered essential by many Brazilian metropolises. This ordinance was meant for municipalities with 700,000 inhabitants. Later, the Brazilian government expanded the PAC program to smaller municipalities.

According to this ordinance, public transport projects must benefit mobility of the low-income, promote population densification, promote the articulation of transit, urban traffic and urban planning policies, and integrate transportation with urban and economic development. These qualitative guidelines play a key role on the decision processes (along with environmental, financial and legal principles).

With the PAC investment packages, Brazil changed its Urban Mobility policy framework. In 2012 a National Policy for Urban Mobility (Law 12.587/2012) was approved, that requires all municipalities above 20K inhabitants to have an Urban Mobility Plan. Municipalities that do not satisfy this requirement cannot receive future federal urban mobility funds, e.g. PAC funds. This law became a major guidance in Brazil with two directives focusing on the land use-transport issue: one about the integration of urban mobility policies and land use management; and other about the prioritization of public transport projects that induce, and structure integrated urban development. Law 12.587/2012 and these two directives were later adopted by the Ministry of Cities as part of their selection process for funding.

As mentioned before, the Brazilian Ministry of Cities also asks for project sponsors to take into consideration on their proposals, projects that contribute to structuring the development of urban space and that are coordinated with available urbanistic instruments. They are also concerned with the social impact of projects, asking project sponsors to detail the mobility benefits of transit projects on low-income population, as well as on helping families who might be subject to displacements in the intervention areas. Public transport projects must work as the backbone for integrated urban development, and improve local urban conditions in the intervention areas.

For evaluation purposes, the Ministry of Cities asks for a significant amount of information, but does not publishes a formal rating process. Instead they give recommendations through workshops and publications (Ministério das Cidades, 2015a, 2015b) about how to design state-of-the-art public transport systems and Urban Mobility Plans.

3.6.3. Metro do Porto

When compared to the US and to Brazil, Portugal is a small country, with its largest metropolitan area housing less than 3 million inhabitants. Nevertheless, in recent years a substantial transformation has occurred in Lisbon and in Porto metropolitan areas: the construction from scratch of two LRTs (Metro Sul do Tejo, and Metro do Porto) and further extensions of Lisbon's subway system. The regulatory framework regarding public transport investment projects was prepared for each project and, in this review, the case of Porto is discussed.

Metro do Porto is an unprecedented undertaking for Portugal and Europe: a LRT system that in a timespan of less than 20 years launched an international public tender and delivered 6 lines, 81 stations, and 67 km of light rail network (Metro do Porto, 2016; Pinho and Vilares, 2009). The tendering process covered design, building, operation and equipment, and the proponents had to obey specifications concerning aspects such as the "insertion in the urban fabric" and the "impact over the regional economy" (Tavares and Antunes, 2000). These two criteria are the closest to the land use and economic development concerns. Figure 26 presents the evaluation tree with weighting used in this process.

The tender specifications provided neither quantitative thresholds nor rating scales, but rather a set of qualitative aspects to be followed by the proponents. Among the qualitative aspects under the "Insertion in the urban fabric" criterion, the adoption of architectural solutions that create value to new and existing urban spaces, as well as the creation of structures that work as a "catalyst" of new urban references, reflect the concerns of decision-makers in relation to the impact of the LRT system on land use. For the "impacts over the regional economy" criterion, the qualitative aspects reflect the importance of the new system on the regional economic development, and on direct and indirect job creation.

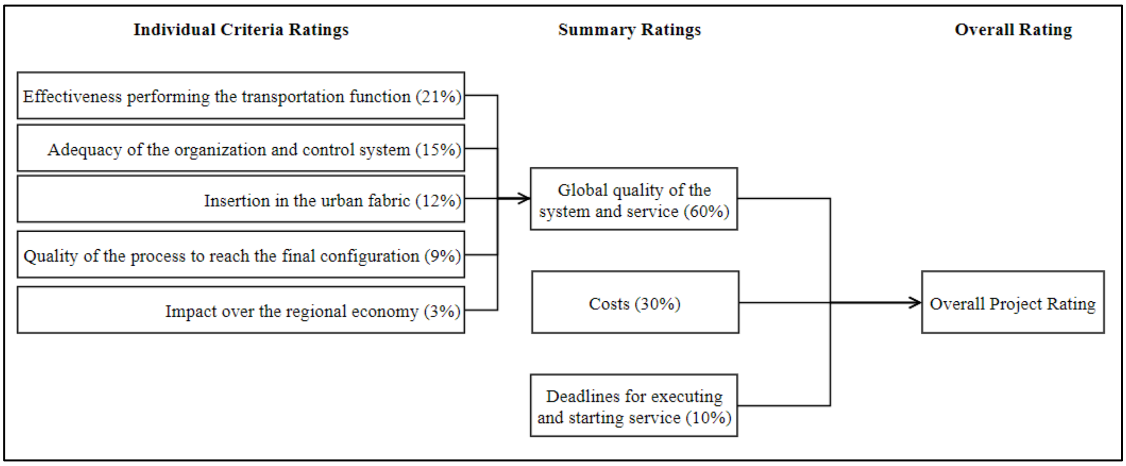

Figure 26 - Metro do Porto decision process (Source: Tavares and Antunes, 2000).
Note: Individual Criteria Ratings only sum up to 60%.

3.6.4. Evaluation of the approaches

In this sub-section, we start by briefly assessing the decision approaches, in terms of their quantitative and qualitative specifications. Further we analyze how the decision processes incorporate and value changes in land use and, finally, conclude with an overall assessment (Table 23) of these processes.

In quantitative terms, the American decision process clearly outranks the Brazilian and the Portuguese processes. By presenting quantitative breakpoints for current and future land use and economic development conditions. FTA's decision process helps project sponsors to know exactly at which level their projects fit in, leading to a more transparent decision process.

For qualitative specifications, on the other hand, the three countries present a medium to high level of detail. For the Brazilian case, concerns about land use, and the social and economic development impacts of projects, are addressed through qualitative recommendations supplied by an ordinance. Moreover, a "Displacement Plan and Measures of Compensation" must be produced when such situations happen. Still in the Brazilian case, Brazil's Urban Mobility Law requires all municipalities above 20k inhabitants to have an Urban Mobility Plan. By binding this requirement with future urban mobility funds, Brazilian officials ensure future project proposals a higher level of commitment on improving urban mobility instead of just building isolated or misplaced transit infrastructure.

For the Portuguese case, Metro do Porto's tender specifications defined a set of precise qualitative aspects, to be followed by the proponents. However, again FTA's approach stands out, presenting a thorough framework that complements quantitative specifications with further, more detailed, qualitative specifications. It also specifies how to obtain such data.

All three decision processes qualitatively appreciate projects serving, traveling through or helping to promote dense mixed-use zones rather than low-density single-use zones, but FTA quantitatively values projects that run through or promote TOD through planning as well.

In terms of land prices, and the increase of rents and sale prices residential and commercial properties nearby transit stations might experience, Brazil and Portugal do not include or specify how to address the issue. On the other hand, FTA does care about the increase in land prices by appreciating projects proposals that circumvent such impact and ensure affordable housing at station areas. Property value increases can help finance transit systems through value capture mechanisms that can be incorporated on CBA as a cash influx that can help pay system costs. However, the USA prefer avoiding such gains: tools to maintain or increase the share of affordable housing are rated highly quantitatively and qualitatively by FTA standards. The reason for that might be related to the fear of gentrification. Table 23 presents a summary of these observations.

Table 23 - Summary of the decision processes

Entity	FTA	PAC	Metro do Porto
Level of specifications			
Quantitative	High	Low	Low
Qualitative	High	Medium	Medium
Land use changes			
Mixed-use and density	Incorporates in the decision process	Incorporates in the decision process	Incorporates in the decision process
Property prices	Incorporates in the decision process	-	-

3.7. Conclusions and further research

This chapter covered a couple of topics on the incorporation of land use changes in capital investment transit decision-making. After introducing the theoretical feedback cycle between land use and transport, and stressing that some transit systems might affect more land use than others due to their perceived sense of permanence, four metrics covering land use changes induced by transit investment were reviewed: accessibility, density, mixed-use and property prices. These metrics have been defined, and ways to forecast and compute them were discussed.

Forecasting land use changes is a complex procedure that demands sophisticated models and methods, such as LUT, hedonic or GWR models. This might be one of the reasons for seldom employing land use changes on transit decision-making. Moreover, these changes have problems that hinder their potential to be incorporated in decision-making: they carry considerable uncertainty (specially changes in property prices), they are hard to monetize and evaluate, and might be ignored to avoid double counting. Nonetheless some tools for tackling those issues were debated: TOD plans and value capture mechanisms. These tools can work together, as well.

Value capture takes part of the gains from properties back into the system, while TOD plans ensure that zoning laws near stations will favor dense and mixed land use patterns which, in the medium/long term, will help increase station ridership. Instead of trying to estimate the changes on mixed-use and density caused by transit investment, the municipality enacts a TOD plan. Hence, the TOD plan is evaluated, for instance with MCDA. In that way, the decision-maker knows, to a certain degree, that mixed-use and density changes will happen, even if he is not able to estimate their values. However, as stated by Börjesson et al. (2014), coupling land use and transit planning can be difficult, because responsibilities and decision power are divided between actors. A similar concern exists with value capture, as it requires some articulation between different actors, to guarantee its application. Hence, a new decision system that incorporates land use changes without the need of TOD plans or value capture mechanisms is necessary.

The literature shows there is a growing interest on the subject by researchers (Bertolini et al., 2005; Damart and Roy, 2009; Geurs and van Wee, 2004; May et al., 2008; Polzin and Baltes, 2002; Thomopoulos and Grant-Muller, 2013; TRB, 2007; Vuchic, 2007), while formal government decision support systems still lack uniform approaches to deal with such issues. In the three cases analyzed (from Brazil, Portugal and the USA), a variety of methods try to address land use issues quantitatively or qualitatively.

The current number of employees served by the system, the population density, the parking supply and the level of affordable housing are quantitative and qualitative metrics appraised by the American decision system, along with potential future commercial, residential, parking and affordable housing developments.

The Brazilian decision system limit the evaluation to qualitative specifications, valuing projects that benefit mobility of the low-income; increase population densification; promote the articulation of transit, urban traffic and urban planning policies; and integrate transportation, urban and economic development.

The Portuguese decision system also limit the evaluation to qualitative specifications, valuing projects that create value to new and existing urban spaces; create structures that work as a "catalyst" of new urban references; play a role on regional economic development; and on direct and indirect job creation.

Further research should investigate diverse ways of incorporating land use changes on transit decision making that do not require TOD plans, value capture mechanisms or sophisticated LUT models. This could be done with a MCDA approach. Stakeholders can be interviewed to see how they value such criteria and how those criteria weight on the final choice.

4. A DECISION SUPPORT SYSTEM FOR INVESTMENTS IN PUBLIC TRANSPORT INFRASTRUCTURE

- Introduction and DSS requirements
- Definition of criteria and subcriteria
- Land use and transport models
- Value functions
- Sensitivity analysis
- An illustrative small case study
- Conclusions

4.1. Introduction and DSS requirements

As presented in chapter 3, there are several approaches for understanding and handling land use changes, in terms of decision-making processes for transportation systems. These approaches are used in more theoretical research, in academic environments (Banai, 2010; Bertolini et al., 2005; da Silva et al., 2008; Hull et al., 2012; Thomopoulos and Grant-Muller, 2013) and in practice, by government funding agencies (e.g. Ministry of Transport) (FTA, 2015; MacKie and Worsley, 2013). They can be summarized as follows:

- political/planning approaches: value capture mechanisms, and Transit Oriented Development (TOD) plans;
- methodological/modeling approaches: Land Use and Transport (LUT) models, and evaluation at face values.

Value capture takes part of the gains from surrounding properties back into the system, and these gains can then be evaluated with traditional CBA as a capital influx (Levinson and Zhao, 2012). TOD plans ensure that zoning laws near stations will favor dense and mixed land use patterns that, in the medium/long term, will help increase station ridership. Instead of estimating and evaluating the changes caused by transport investments on land use, the TOD plan is evaluated, for instance with MCDA techniques (FTA, 2015). In that way, the decision-maker knows, to a certain degree, that the changes will happen, even if their impacts are not fully estimated. On the other hand, LUT models do estimate changes in land use triggered by transit systems, typically based on project development catalogs and hedonic models, and update baseline population and activity data, that are typically the inputs for four-step models – this process is iterated several times, and then the evaluation is performed. Other metrics (such as accessibility), evaluated at their face value, by MCDA-type methods, are less common in the literature (Hull et al., 2012).

TOD plans can be difficult to implement, because responsibilities and decision-making are fragmented (Börjesson et al., 2014). Value capture approaches can also be difficult to use, as they demand some articulation between different stakeholders to guarantee their application (Martínez, 2010). On the other hand, LUT models are also somehow challenging as they are rather sophisticated, data intensive, and expensive to build and to keep updated. Hence, an innovative DSS, incorporating land use changes, not requiring TOD plans, nor value capture mechanisms or sophisticated LUT models, may be a quite valuable tool, in practical terms.

This chapter presents a DSS that incorporates land use changes (this system can be viewed as the main contribution of the thesis). Considering the research questions, objectives and literature review, the DSS is developed based on the following requirements:

A. The investment alternatives are defined a priori

The DSS alone will not be able to find the optimal solution (even using tools from operations research or transport modeling). To define a set of alternatives, the decision-maker, with the help of analysts, performs some preliminary studies, thus defining the features of each alternative, such as routes, frequencies, type and capacity of vehicles, and spacing between stations. After that, the DSS will test the investment alternatives proposed and rank those alternatives, from best to worst. However, sensitivity analysis might propose changes in the investment alternatives' features to improve performance.

B. Land use changes must be incorporated along with more traditional decision parameters

The decision parameters must be simple, concise, exhaustive and non-excessive. They must be presented in an organized and structured way, easy for public discussing and participation.

C. An efficient way of forecasting land use changes must be proposed

Considering that the complexity associated with modeling and forecasting land use changes is a major reason for overlooking these changes on decision-making, an efficient model must be proposed to overcome this hindrance and properly structure the decision-making process.

D. The decision parameters must contribute to evaluating each alternative

Each investment alternative must be assigned a final score that should result from the combination of the decision parameters (in a *utility-based* approach).

E. To develop a DSS suitable to multiple decision contexts, independent expert opinions must be incorporated

Rather than relying on the decision-maker opinion, which might lead to bias favoring one investment alternative over another, experts are consulted without knowing in detail the investment alternatives beforehand.

F. Risk and uncertainty must be incorporated

Sensitivity analysis must be carried out before delivering the final rank of alternatives.

These requirements will help choose the base evaluation method of the DSS. To address requirement A, both CBA and MCDA are suitable evaluation methods, however, on requirement B, CBA is discarded, as it demands monetization of costs and benefits, which does not seem an appropriate way to evaluate land use changes. Despite many costs and benefits being easy to monetize, monetizing land use changes through a willingness-to-pay survey could bring false certainty (Beukers et al., 2012), therefore these costs and benefits should be analyzed through a non-monetized approach that considers their face values. Moreover, acquiring and modeling the willingness-to-pay can be burdensome and costly. Hence, MCDA is chosen as basic method to build up the DSS.

Requirements D and E point to the development of a *value function* (Bana e Costa and Vansnick, 1994; Vincke, 1992). Value functions (deterministic utility functions), are part of multi-attribute utility theory (Belton and Stewart, 2001; Vincke, 1992), a MCDA branch. They are the summation of attributes multiplied by weights, resulting in a final score for each investment alternative:

$$V(A) = k_1 * a_{A1} + k_2 * a_{A2} + k_1 * a_{A3} \dots + k_m * a_{Am}$$

where $V(A)$ is the final score of alternative A, k_1 is the weight of decision parameter 1, a_{A1} is the attribute (i.e. the result) of decision parameter 1 for alternative A, and m is the total number of decision parameters.

Value functions incorporate independent points of view from experts (i.e. the weights) and the results of the decision parameters (i.e. the attributes), to deliver a score, leading to the numerical assessment of the final ranking of each investment alternative. This is a way to measure the distance between investment alternatives and to estimate the level of advantage of one alternative against another (Ambrasaite et al., 2011).

To be able to use additive value functions, preferential independence (Vincke, 1992) must be checked. The experts should not change their weights due to the presence of a given alternative, e.g. they will not prefer a cheaper but slower BRT over a costly but faster LRT. All decision parameters need to be independent, because the experts do not know beforehand the alternatives in detail (requirement E).

Expert opinions are reflected on the weights. To obtain such weights, a survey is developed.

This DSS will also allow a final sensitivity analysis (requirement F), that must consider endogenous and exogenous uncertainties. Finally, requirement C is addressed by an efficient land use model to estimate the impact caused by the presence of a transit station in the surrounding land use.

The system was designed to guide decision-makers through the decision process, so that, at the end, the final choice is sound and trustworthy.

It is intended to support decision-making, and it should not replace the economic and financial assessment of investments, but rather complement these types of analysis. The main inputs for the system are the investment alternatives, and its structure is depicted in Figure 27.

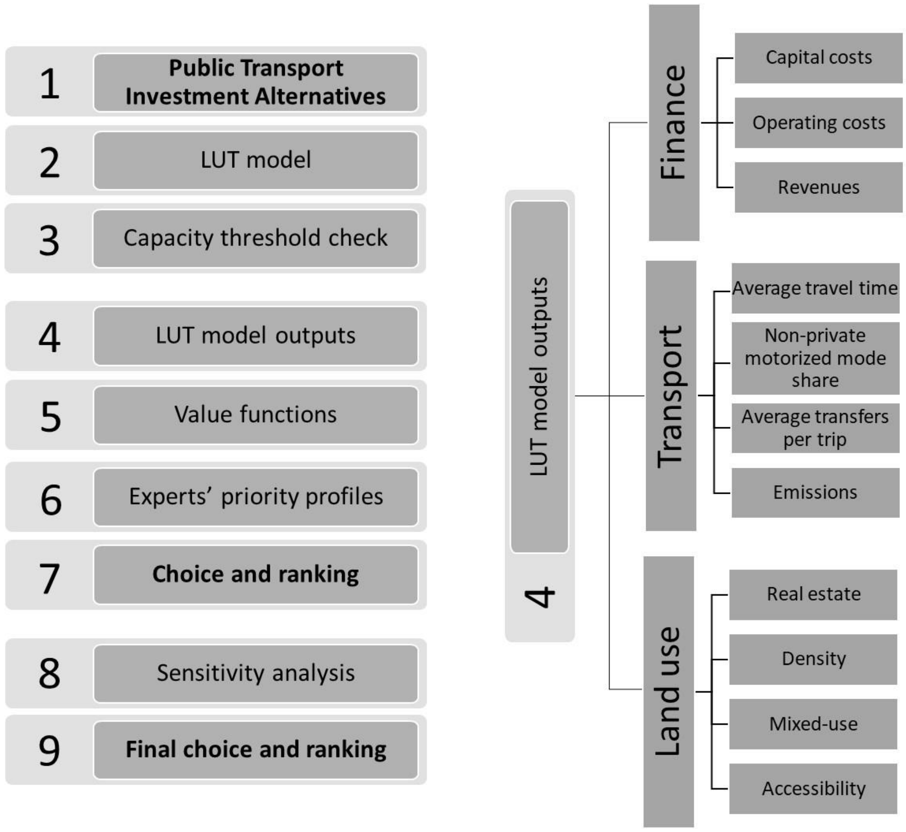

Figure 27 - The DSS structure

After this introduction, where the DSS requirements and structure were briefly presented, the following sections of this chapter will cover: the definition of criteria and subcriteria (4.2); the land use and transport models (4.3); the value functions (4.4); and the sensitivity and risk analysis (4.5). Before concluding the chapter (4.7), a global description of the DSS operation and its application to a small illustrative case study (4.6) are presented.

4.2. Definition of criteria and subcriteria

After a comprehensive review of the literature (chapters 2 and 3), the following decision parameters were elected as essential for decision-making: capital costs; operating costs; revenues; travel time; emissions; accessibility; density; mixed-use; and real estate. Non-private motorized mode share and transfers were added as well: mode share reflects growing concerns regarding the need for more sustainable and balanced transport systems (Banister, 2008; Cervero, 2013; Kenworthy and Laube, 1996), while transfers are a major disutility for the passenger and should be avoided. Similar decision parameters are used in other MCDA tools, as for instance Ambrasaite et al. (2011); Banai (2010); Brunner et al. (2011); Camargo Pérez et al. (2015); Janiak and Żak (2014); Oswald Beiler and Treat (2014); Rabello Quadros and Nassi (2015); Żak et al. (2014).

These decision parameters are here called “subcriteria”, and they accurately reflect the impact transit investments have on finance, transport and land use (henceforth called criteria). This hierarchical organization facilitates public debate about investment alternatives, since it makes it possible to present the decision problem in a structured way to the affected community and to the decision-makers. Figure 28 depicts this organization.

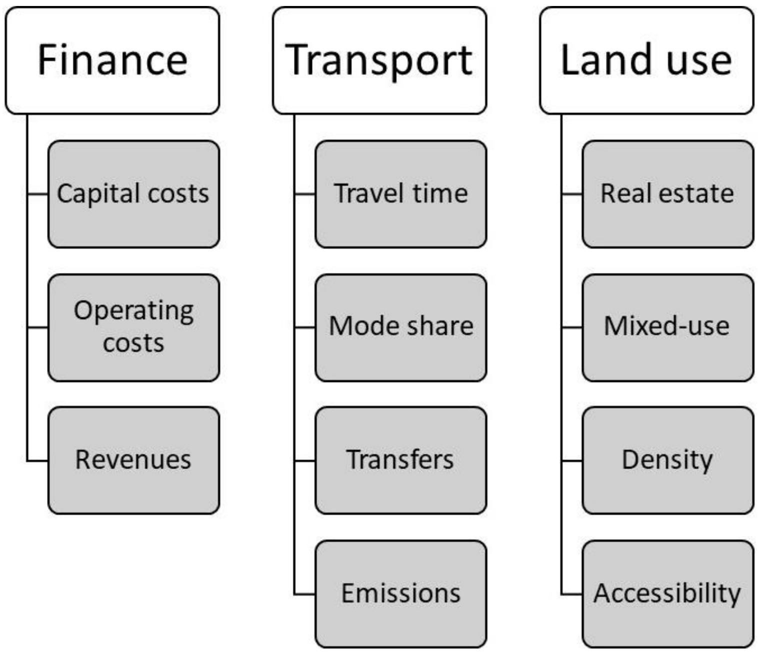

Figure 28 - Hierarchy of criteria and subcriteria

For the finance criterion, three subcriteria commonly employed in decision-making are considered:

1. capital costs represent Infrastructure costs and any related land or property acquisition costs, including vehicle acquisition costs;
2. operating costs represent yearly operating costs of the system;
3. revenues represent the farebox revenues collected during system operating hours.

Under the transport criterion, the following subcriteria are considered:

1. travel time: average morning transit commute time;
2. mode share: share of non-private motorized commute to work, with public transport and walking modes;
3. transfers: average number of transfers per trip;
4. emissions: carbon dioxide emissions.

For the land use criterion, the subcriteria are:

1. real estate: residential property prices per square meter near (1/2 mile) transit stations;
2. density: population density near (1/2 mile) transit stations;
3. mixed-use: entropy index near (1/2 mile) transit stations - 0 (homogeneity, only jobs or only population) and 1 (heterogeneity, jobs and population evenly distributed);
4. accessibility: share of total jobs reachable by transit within 60 minutes.

4.3. Land use and transport models

One of the objectives of this research is to incorporate land use changes on decision-making. One way to come up with those changes is through an integrated land use and transport model (LUT), as discussed in chapter 3. Despite being the state-of-the-art, LUT models take substantial effort to build, are expensive, and data and time-consuming, thus limiting their appeal for use in most decision-making contexts. Constructing a DSS requiring a full integrated LUT model would substantially weaken its usefulness.

To skip the time-consuming task of building such models but still be able to benefit from their advantages, we propose an efficient LUT model, based on a traditional four-step transport model, combined with costs and emissions estimations, and a land use model based on results from the literature, covering changes (i.e. growth indicators) of population, jobs and property prices near an LRT or a BRT station. Accessibility changes are estimated computing travel time and jobs. This is not a typical LUT model, but it still relates, in a more pragmatic way, land use and transport.

4.3.1. The transport model

The classical four-step model (see chapter 2) helps estimate some transport subcriteria and the revenues. While travel time, non-private motorized mode share and transfers are direct results of the four-step model, revenues must consider ridership, that is also estimated by the four-step model. Capital and operating costs and emissions can be estimated with other specific models, or, if not possible, through benchmark values.

4.3.2. The land use model

To estimate real estate, density, mixed-use and accessibility subcriteria, the following "land use model" was developed:

1. get current land use data for each TAZ: population; jobs; area and average residential property prices per square meter (these data can be drawn from census data and real estate databases);
2. compute the same land use data for a station area, i.e. ½-mile buffer around a transit station (about $2km^2$);
3. to estimate future station land use data, growth indicators drawn from literature are applied over the current station area land use data. (see Table 24);

Table 24 - Growth indicators

Land use feature	Transit System	Growth (%)	References
Population	BRT	10	Bocarejo et al., 2013
	LRT	7	Bhattacharjee and Goetz, 2016
Jobs	BRT	50	Kang, 2010
	LRT	17	Banister and Thurstain-Goodwin, 2011
Residential property prices	BRT	7.6	Perk et al., 2013
	LRT	3	Diao, 2015

4. with future land use data, it is possible to compute: the average residential property price per square meter (for the real estate subcriterion); an entropy index with future population and job totals (for the mixed-use subcriterion); the population density (for the density subcriterion);
5. only accessibility is based on current jobs data instead of future jobs, as this is a conservative approach avoiding potential uncertainty from job forecasting (jobs and travel times are then combined with an isochrone-based measure (see chapter 3), a metric that is easy to read and understand by non-experts).

The residential property prices growth indicators presented in Table 24 were based on estimates for the Boston transit system (namely for the *Silver Line BRT* and the *Green line LRT*), a system that is very familiar to us and that is subject of analysis in chapter 5. Regarding job and population growth, the literature regarding quantitative empirical studies is scarce. Most of the research is either qualitative or oriented towards land uses and not to population or jobs: it is common to estimate growth in new apartments and retail activity (Badoe and Miller, 2000; Cervero and Kang, 2011; Deng and Nelson, 2010) but not growth in residents or workers. However, Bocarejo et al. (2013) and Bhattacharjee and Goetz (2016) report a population growth up to 10% and 7% at BRT and LRT station areas, respectively, while Kang (2010) and Banister and Thurstain-Goodwin (2011) report an employment growth up to 50% and 17% at BRT and LRT station areas, respectively. These growth indicators reflect very different land use and transport patterns, resulting from various modelling methods and assumptions. Thus, it is important to apply them with caution, and a sensitivity analysis, where one can change and test other growth indicators, is recommended.

Regarding the duality raised in this thesis about the possibility of land use changes, triggered by transit investment, being a value transfer instead of value creation, it is important to emphasize that we considered that new transit investment will create new value.

4.4. Value functions

4.4.1. Normalization with market values

The results from the land use and transport model, and any other auxiliary method used, will be inputted as attributes in the value functions. A typical issue that emerges when using value functions is the many measurement units of the attributes, e.g. costs in monetary units, or travel time in minutes. By simply multiplying each attribute value by a weight, and then summing all up, would therefore, yield incorrect results. Thus, the attributes must be normalized to the same scale, before entering the value functions.

The normalization process normally consists in setting a scale from 0 to 1, where 0 represents the worst value and 1 the best value[12]. This scale can take multiple forms, and a linear pattern is here

[12] The "best" and "worst" terminologies used in this work strictly refer to the best and worst market values (i.e. the lower or the upper bounds of the market value sample), and not the best and worst

adopted, this meaning the decision-maker, for a given subcriterion, values equally the same "amount" of change whatever the absolute figures are – e.g. a capital cost reduction from 35 to 5 is equal to a reduction from 65 to 35 (this making the situations indifferent). To define the scale boundaries, exogenous samples of market values are collected for each subcriterion, creating a robust benchmark. The next sub-sections describe this process, its sources and some statistics from the samples.

The benchmarks were taken from recent BRT and LRT projects in the US (FTA, 2016a) and on general transport and land use data from US metropolitan areas (Accessibility Observatory, 2014; FHA, 2009; FTA, 2010; U. S. Census Bureau, 2014; Zillow, 2016). A summary of the data used in this work can be found in Table 25 and in the Appendix.

4.4.1.1. Capital costs

From a total of 38 BRT and LRT projects in FTA'S database (FTA, 2016a), 33 projects (19 BRTs and 14 LRTs) present the estimated capital costs and the corridor length, allowing the computation of the capital cost per kilometer. All projects consider vehicle acquisition on capital cost estimations.

4.4.1.2. Operating costs

From a total of 38 BRT and LRT projects in FTA'S database (FTA, 2016a), 18 projects (10 BRTs and 8 LRTs) present the estimated operating costs per year, typically for the opening year, and the corridor length, allowing the computation of the annual operating cost per kilometer.

4.4.1.3. Revenues

From a total of 38 BRT and LRT projects in FTA'S database (FTA, 2016a), 16 projects (5 BRTs and 11 LRTs) present estimated daily ridership for the Horizon year[13] and corridor length, allowing the computation of the daily ridership per kilometer. Ridership is counted as linked trips, meaning a door-to-door trip, regardless of transfers.

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values possible for a given subcriterion (e.g. it is possible to find an investment alternative with a higher capital cost than the "worst" capital cost drawn from the market value sample).

[13] Horizon year is a moment in the future, typically 10 or 20 years after the system started operating.

4.4.1.4. Travel time

To estimate the transit travel time, a second source is combined with FTA'S database (FTA, 2016a): the *2009 National Household Travel Survey* (NHTS) (FHA, 2009). From this database, the average person commute trip length and duration are extracted for all US metropolitan areas with BRT or LRT projects on FTA's database (27 projects: 12 BRTs and 15 LRTs). With trip length and duration, it is possible to estimate an average commute speed which is then multiplied by the corridor length, leading to a travel time.

This approach is questionable as few trips go from one end of a corridor to the other end, and trips might start far away from the corridor. Moreover, NHTS does not break down commute data by mode and, as car trips are typically faster and with a higher node share than other modes, travel times might be smaller than expected. However, due to the lack of more accurate sources, this approach was chosen.

4.4.1.5. Mode share

In a different way, non-private motorized mode share tries to reflect urban sustainability concerns and the impact transit investment might have on the city. Therefore, a different database is consulted: the *2010-2014 American Community Survey 5-Year Estimates* (U. S. Census Bureau, 2014). From this database, non-private motorized mode share for all 381 US Metropolitan Statistical Areas (MSA), are drawn.

4.4.1.6. Transfers

The values used for "transfers" resulted from internal discussions of our research group, as no other experts could be consulted.

4.4.1.7. Emissions

To estimate Carbon Dioxide (CO_2) emissions, a different source was consulted: FTA's document from 2010 - *Public Transportation's Role in Responding to Climate Change* (FTA, 2010). This report provides emissions data in pounds of CO_2 per passenger mile for 50 Bus and 29 LRT systems, with no differentiation between standard bus systems and BRT.

4.4.1.8. *Real estate*

To estimate residential property prices per square meter near (½ mile) transit stations, a second source is combined with FTA'S database (FTA, 2016a): the *Zillow*'s median residential value per square feet, from January 2016 (Zillow, 2016). From this database figures are extracted, and converted to price per square meter, for all US metropolitan areas with BRT or LRT projects on FTA's database (38 projects: 22 BRTs and 16 LRTs).

4.4.1.9. *Density*

From a total of 38 BRT and LRT projects in FTA'S database (FTA, 2016a), 19 projects (11 BRTs and 8 LRTs) present the population density within ½ mile of the proposed station areas.

4.4.1.10. *Mixed-use*

From a total of 38 BRT and LRT projects in FTA'S database (FTA, 2016a), 18 projects (11 BRTs and 7 LRTs) present the population density within ½ mile of the proposed station areas, as well as the number of stations and total employment within the same areas.

These total areas, with their population density and their employment are used to estimate the entropy index.

4.4.1.11. *Accessibility*

Accessibility data is drawn from the *Accessibility Observatory* database for 2014 (Accessibility Observatory, 2014). This database shows how many jobs are reachable by transit within 60 minutes, as well as the total number of jobs in 46 US major metropolitan areas. With that information, it is possible to estimate the share of total jobs reachable by transit in 60 minutes.

4.4.1.12. *The normalization process*

With the market values at hand, the normalization process can be completed. To avoid extreme and unrealistic values, the lower and upper values are defined as, approximately, the percentiles 25 and 75 of the samples. For a subcriterion where a higher value is preferred, e.g. revenues, the upper value is assigned a 1 and lower value, a 0. For a subcriterion where a smaller value is preferred, e.g. travel times, the upper value is assigned a 0, and the lower, a 1 (see Table 25).

To illustrate the normalization process with an example, alternative A has a capital cost of US$ 20 million per km, and alternative B has US$ 35 million per km (see Figure 29).

Table 25 - Market values

Subcriteria	Units	N	Object	Mean	St. Dev.	Min.	Percentile			Max.	Market Values	
							25	50	75		Best	Worst
Capital costs	M US$/km	33	BRT and LRT projects	70.6	129.6	0.9	5.0	12.0	65.4	576.9	5	65
Operating costs	M US$/year/km	18	BRT and LRT projects	0.6	0.5	0.1	0.2	0.3	1.0	2.0	0.2	1.0
Revenues	K trips/day/km	16	BRT and LRT projects	6.5	9.2	206	1.5	1.9	6.9	33.0	7	1.5
Travel time	minutes	27	BRT and LRT projects	22	13	4	10	23	31	47	10	30
Mode share	%	381	US MSA	10%	5%	3%	7%	9%	12%	43%	15	5
Transfers	Nº of transfers	-	Expert Opinion	1.5	1.5	0	-	-	-	3	0	3
Emissions	grams CO_2/pax.km	79	Bus and LRT projects	191	162	36	117	164	206	1 202	100	200
Real estate	US$/m^2	38	BRT and LRT projects	2,517	2,250	635	1,033	1,663	3,014	9,741	3,000	1,000
Density	Population/km^2	19	BRT and LRT projects	4,374	9,084	734	1,409	1,853	2,896	42,471	3,000	1,500
Mixed-use	Entropy	18	BRT and LRT projects	0.84	0.25	0.24	0.81	0.98	0.99	1.00	0.9	0.7
Accessibility	%	46	US Metro Area	9%	5%	2%	5%	7%	11%	25%	15	5

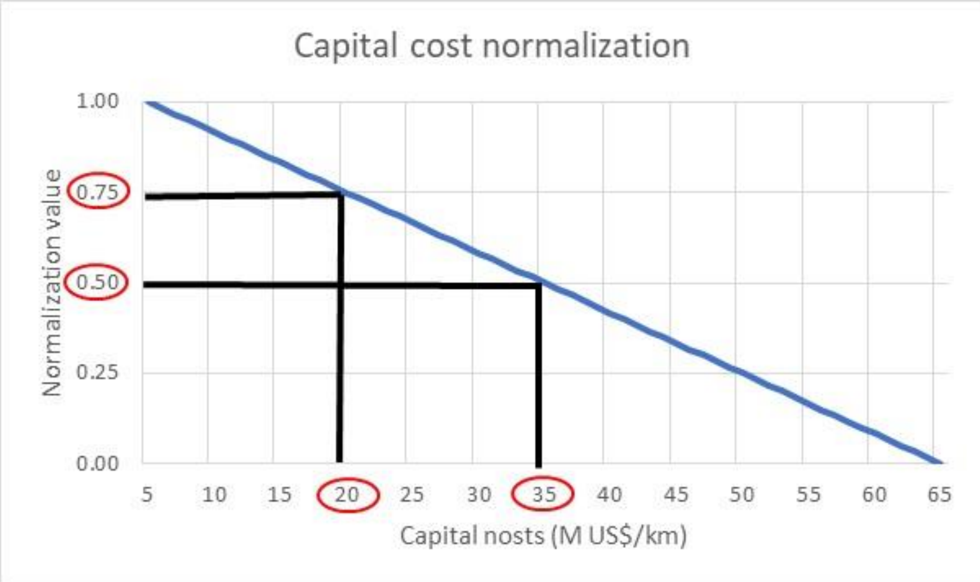


Figure 29 - Linear normalization

4.4.2. Experts' priority profiles

The value functions require that weights are assigned to the different attributes[14]. Simply asking experts or the decision-maker for the weights is a process that should be avoided, as it can lead to considerable uncertainty and biased responses. Hence, some methods can aid on determining these weights, as e.g. MACBETH, TOPSIS, ELECTRE and Promethee (Camargo Pérez et al., 2015; Janiak and Żak, 2014; Rabello Quadros and Nassi, 2015; Vincke, 1992). However, the Analytic Hierarchy Process (AHP) (Saaty, 1987) was chosen for our survey. AHP is widely employed in transportation and it is present in a large number of scientific publications (Brunner et al., 2011; Camargo Pérez et al., 2015, 2015; Rabello Quadros and Nassi, 2015). The AHP framework is very adequate to decision problems arranged in a hierarchical and transparent structure (Banai, 2006; Janiak and Żak, 2014).

The AHP method has a 9-point scale for pairwise comparison (Saaty, 1987) and, through a specific procedure, it compares all criteria against each other, and all subcriteria, within the same criteria umbrella, against each other, leading to a comparison matrix and consistency ratios[15] (CR). From

[14] Henceforth called LUT model outputs or simply outputs. The outputs are produced by the LUT model, which encompasses not only the land use and transport model, but also any other auxiliary method or source used to estimate the outputs.

[15] The consistency ratio measures how consistent the answers have been relative to large samples of purely random answers.

this matrix, it is possible to extract the *eigenvector* that represents the weights, to be later used in the value functions. Saaty's AHP method demonstrates that the characteristic vector (or eigenvector) solution is a good method for determining the relative weights that arise from paired comparisons (Banai, 2010).

However, AHP surveys typically compare, pair-by-pair, the criteria and subcriteria "names" and not their potential values. This procedure can be completely detached from the problems at hand and lead to poor weights (Brunner et al., 2011). For instance, comparing travel time savings against CO_2 emissions reductions is different from comparing 2% travel time savings against 90% CO_2 emissions reductions. While a survey respondent will most certainly prioritize (i.e. give more weight) travel time savings in the first case, in the second case he might do the opposite. Hence, the definition of weights should not be independent of the value functions and should incorporate information provided by them. To overcome this hindrance, *swing weights* (Hobbs and Meier, 2012), a methodology that evaluates the changes (increase / decrease) in criteria and subcriteria rather than their names, and the reference market values, are combined on the AHP survey. Rather than comparing criteria and subcriteria names, the variations from worst to best market values are compared. Table 26 presents the survey and the 9-point scale.

The swing weight approach employed in this survey binds the survey results to the market value intervals defined.

The survey was delivered through e-mail to 70 public transportation experts from the academia, consultancy and public sector. The e-mails were sent to each expert, along with a Google Docs spreadsheet containing the survey (see the Appendix for an e-mail example, the survey responses and the detailed list of experts). The e-mails were resent no more than 3 times during a 4-month timespan starting in February 21st and ending in June 21st, 2016. After this period, we stopped asking for more expert responses. At the end, 17 experts answered: 10 from the academia, 5 from consultancy and 2 from the public sector (from Brazil, Canada, Germany, the Netherlands, Portugal and the USA).

Table 26 - The survey

-9	-8	-7	-6	-5	-4	-3	-2	1	2	3	4	5	6	7	8	9
Extremely less important[16]		Very strongly less important		Strongly less important		Moderately less important		As important as		Moderately more important		Strongly more important		Very strongly more important		Extremely more important

Criteria is...than Criteria		
Improvement in Finance		Improvement in Transport
Improvement in Finance		Improvement in Land use
Improvement in Transport		Improvement in Land use

Decrease from 65 to 5M US$/km in capital costs		Decrease from 1 to 0.2M US$/year/km in operating costs
Decrease from 65 to 5M US$/km in capital costs		Increase from 1.5 to 7K trips/day/km in equivalent revenues
Decrease from 1 to 0.2M US$/year/km in operating costs		Increase from 1.5 to 7K trips/day/km in equivalent revenues
Decrease from 30 to 10 minutes in average travel time		Increase from 5 to 15% in non-private motorized mode share
Decrease from 30 to 10 minutes in average travel time		Decrease from 3 to 0 in average transfers per trip
Decrease from 30 to 10 minutes in average travel time		Decrease from 200 to 100 g CO_2/pax.km in emissions
Increase from 5 to 15% in non-private motorized mode share		Decrease from 3 to 0 in average transfers per trip
Increase from 5 to 15% in non-private motorized mode share		Decrease from 200 to 100 g CO_2/pax.km in emissions
Decrease from 3 to 0 in average transfers per trip		Decrease from 200 to 100 g CO_2/pax.km in emissions
Increase from 1,000 to 3,000 US$/$m^2$ in house prices		Increase from 0.7 to 0.9 in mixed-use
Increase from 1,000 to 3,000 US$/$m^2$in house prices		Increase from 1,500 to 3,000 pop/km^2 in density
Increase from 1,000 to 3,000 US$/$m^2$ in house prices		Increase from 5 to 15% in transit accessibility
Increase from 0.7 to 0.9 in mixed-use		Increase from 1,500 to 3,000 pop/km^2 in density
Increase from 0.7 to 0.9 in mixed-use		Increase from 5 to 15% in transit accessibility
Increase from 1,500 to 3,000 pop/km^2 in density		Increase from 5 to 15% in transit accessibility

[16] The negative numbers are computed as inverse in the comparison matrix.

From the survey answers, responses were treated in a “standard” worksheet (Goepel, 2013) (see Appendix), where consistency ratios (CR) and weights are computed. Some CRs exceeded the threshold suggested by Saaty (1987) – CR <0.1. Responses with CR>0.2 were slightly adjusted until reaching a CR<0.2, a limit typically considered as acceptable (Goepel, 2013). Table 27 shows the weights, henceforth called expert’s priority profiles.

Among the criteria, transport gets more than half of the priority, followed by finance and land use. Within the “finance” criterion, “revenues” are prioritized, followed by “operating costs” and “capital costs”. Travel time, mode share, transfers and emissions, are ranked in that order for the “transport” criterion. Finally, for the land use criterion, “accessibility” is the most important indicator, followed by density, real estate and mixed-use. These results somehow complement earlier findings regarding the importance of travel time gains (Mackie et al., 2001), assuring system’s financial sustainability through higher revenues, and increasing focus on the importance of deploying transport solutions which enhance accessibility (Bertolini et al., 2005).

Together with the quantitative responses, some comments were made by the experts:

1. four experts asked for more information to better assign the weights, and found it hard to respond without more information;
2. one expert wanted to know if the alternatives were rail projects;
3. one expert questioned the validity of comparing BRT and LRT;
4. one expert cherished the selection of criteria and subcriteria, as good proxies for decision-making;
5. one expert justified all his answers.

Comments 1, 2 and 3 are worth addressing. Comment 1 stresses that, despite using the swing weights methodology and market values, the survey should also have data about the investment alternatives. However, by doing that, the preferential independence condition could be violated, leading to biased responses. The first page of the survey and the e-mail (see Appendix) specified that alternatives are BRT and LRT, thus responding to comment 2. As described in chapter 2, BRT and LRT are somewhat comparable, due to similarities in their features. This argument was used to respond to the expert responsible for comment 3.

Table 27 - Expert's priority profile

Criteria	Subcriteria	Mean	St. Dev.	Min.	Percentile			Max.	Final Weights	Equivalent weights	Order of Priority
					25	50	75				
Finance		28.5%	16.3%	9.1%	15.7%	25.8%	40.0%	73.1%	27.3%		
	Capital cost	23.8%	18.0%	8.6%	10.5%	16.7%	31.1%	65.7%	21.7%	5.9%	9th
	Operating cost	33.3%	17.0%	10.0%	19.6%	29.7%	48.1%	61.8%	33.0%	9.0%	4th
	Revenues	42.9%	18.4%	14.7%	31.9%	35.1%	61.8%	80.0%	45.3%	12.4%	2nd
Transport		50.2%	15.3%	11.3%	45.5%	54.0%	62.5%	70.1%	52.4%		
	Travel time	39.7%	19.0%	12.7%	22.5%	39.4%	58.1%	69.8%	42.7%	22.4%	1st
	Mode share	24.4%	15.7%	2.8%	12.3%	21.8%	37.0%	57.5%	23.5%	12.3%	3rd
	Transfers	18.1%	15.5%	6.0%	8.4%	12.1%	19.9%	58.1%	17.0%	8.9%	5th
	Emissions	17.8%	12.7%	5.0%	6.8%	13.1%	26.3%	43.3%	16.8%	8.8%	6th
Land use		21.3%	13.1%	7.7%	10.5%	15.1%	28.6%	50.8%	20.2%		
	Real estate	21.2%	17.9%	4.8%	7.5%	13.1%	27.7%	65.8%	18.1%	3.7%	10th
	Mixed-use	17.6%	11.2%	2.8%	5.2%	14.7%	29.5%	35.5%	15.7%	3.2%	11th
	Density	30.5%	16.0%	8.4%	18.3%	30.0%	38.0%	67.1%	31.3%	6.3%	8th
	Accessibility	30.8%	9.4%	11.8%	25.0%	30.0%	35.5%	55.4%	34.9%	7.1%	7th

4.5. Sensitivity analysis

As described in chapter 2, sensitivity analysis is a way to test the robustness of the final choice and ranking, in the presence of uncertainty and risk. Normally, the risk situations are considered different from the uncertainty cases, because we can assign a probability to the different possible outcomes. In this work, we use "uncertainty" as a general term for describing situations that are non-deterministic and thus can affect the final outcomes. Our DSS handles uncertainty of different types as described in the following sections.

4.5.1. Uncertainty in the modeling process and inputs

What changes in the modeling process and inputs would lead to changes in the ranking of the alternatives?

Some subcriteria (for instance, travel time, capital and operating costs and revenues) are frequently over or underestimated. Moreover, land use subcriteria, mainly real estate might be over or underestimated (Higgins and Kanaroglou, 2016). Therefore, they should be tested considering their probability of being misestimated.

4.5.2. Different normalization processes

How does the normalization process influence the ranking?

Different normalization functions (e.g. exponential) should be tested, as the decision-maker might not want to value equally the same differences in the values of certain subcriteria.

4.5.3. Different priority profiles

How does the priority profile influence the ranking?

We should be able to test different priority profiles reflecting market or policy pressures – e.g. preferences for cheaper alternatives (a *financial-constrained* case) or preference for alternatives that boost urban development (an *urban-friendly* case). Priority profiles might also be changed to reflect the risk the decision-maker is willing to take. Some subcriteria are more uncertain than others and can change over time, so the decision-maker may not want to take the risks of choosing one alternative with low costs and high benefits, with substantial uncertainty associated, and rather prefer a more conservative alternative with less uncertainty associated.

4.5.4. A rule of thumb for sensitivity analysis

Several uncertainty scenarios can be proposed, possibly leading to different final choice and rankings. Part of these scenarios can be simply ignored by the decision-maker or, with the help of some rule of thumb or decision paradigm, might be accepted for future analysis. To help deciding, Matos (2007) approach is adopted on our DSS:

1. in a set of scenarios with probability associated, a graphic combining the expected score and the worst score might be useful for evidencing nondominated alternatives;
2. in a set of scenarios without probabilities, the minimax regret approach is adopted.

4.6. An illustrative small case study

4.6.1. The decision process

As presented in Figure 27, the decision process is structured around 9 steps (roughly associated to different components of the DSS). In a first step (Public Transport investment alternatives), in order to define a set of alternatives, the decision-maker, with the help of analysts, performs some preliminary studies, thus defining the features of each alternative, such as routes, frequencies, type and capacity of vehicles, and spacing between stations. Next, the alternatives are inputted into a LUT model with two parts: a classic four-step transport model, and a land use model that estimates real estate, mixed-use, density and accessibility changes. To obtain these changes, growth indicators around stations were drawn from the literature, reflecting the impact caused by a station in the use of adjacent land. The LUT model (combined with other auxiliary methods or sources) also produces seven other outputs: capital costs; operating costs; revenues; average travel times; non-private motorized mode share; average transfers per trip; and carbon dioxide emissions. Before moving to the decision process itself, a capacity verification is performed, ensuring all alternatives meet a pre-established in-vehicle load factor to qualify for further evaluation.

The next steps help decide which investment alternative is the "best”: LUT model outputs; value functions; experts’ priority profiles; and choice and ranking of alternatives. The eleven subcriteria are divided into three main groups (criteria): finance; transport; and land use (step 4). Considering that each subcriterion has different units of measure (e.g. costs in euros, travel time in minutes), they must be brought to a common valuation scale. Accordingly, value functions are created for each alternative, using market benchmarks, to end up yielding normalized values (typically between 0 and 1) for each subcriterion (step 5). In step 6, the value functions receive the information obtained from the experts' priority profiles, namely the "weights" for each criterion and subcriterion. Priority profiles are defined by experts through a survey, based on the AHP method and their 9-point scale for pairwise comparison. The entire process helps us in ranking the projects, and in making a choice (step 7).

In step 8, a sensitivity analysis is proposed, before the final decision is made (step 9). This sensitivity analysis is an important procedure to verify how endogenous and exogenous uncertainties can affect the final choice (Clemen and Reilly, 2013), also serving as a way to test the robustness of the final choice.

Finally, the analyst and decision-maker must define a horizon year for the model, typically 10 years after operations have started.

4.6.2. Case study

Before being tested in a real case study (chapter 5), the DSS is first tested in a small, illustrative case study, specifically designed for experimental purposes – an urban area, with around 60 000 inhabitants and 40 000 jobs, distributed in 5 TAZs, and with 5 alternatives for public transport investments: "No Build" (i.e. no interventions), two BRT projects and two LRT projects.

4.6.2.1. Step 01 - Definition of investment alternatives

"No Build" has a bus network, while the other alternatives have a BRT or an LRT system replacing the buses. All alternatives have car and pedestrian modes and, for each alternative, specific features such as the distance between stations, frequency, vehicle capacities, speed and acceleration are known (see Table 28).

Each alternative is also characterized by the land use growth indicators around the stations, for the land use model. The car mode allows direct connections between all zones, except intra-zonal connections (assumed to be made exclusively on foot). In each alternative – No Build; BRT1/2; and LRT1/2 – the modes are respectively bus, BRT, and LRT. Car and walking modes are present in all alternatives, as well.

Table 28 – Features of investment alternatives

Line Names	**NB1**	**NB2**	**A**	**B**	**C**	**D**	**E**	**F**
Mode	Bus	Bus	BRT	BRT	BRT	LRT	LRT	LRT
Paths (TAZs)	2_1_5	3_1_4	2_1_5	3_1_4	2_3_5_4_2	2_1_5	3_1_4	2_3_5_4_2
Station distance (m)	350	350	700	700	700	700	700	700
Length (km)	7.3	7.3	7.3	7.3	14.0	7.3	7.3	14.0
Nº Stations	21	21	10	10	20	10	10	20
Dwell time (sec)	45	45	30	30	30	30	30	30
Frequency (min)	30	30	10	10	10	10	10	10
Vehicle Capacity (pax)	130	130	250	250	250	400	400	400
Fare (€/trip)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Top Speed (km/h)	30	30	50	50	50	70	70	70
Acceleration (m/s2)	0.5	0.5	1	1	1	1.2	1.2	1.2
CO_2 emission (g/pax.km)	180.52	180.52	180.52	180.52	180.52	118.94	118.94	118.94
Residential property price growth	0	0	7.6%	7.6%	7.6%	3%	3%	3%
Population growth	0	0	10%	10%	10%	7%	7%	7%
Job growth	0	0	50%	50%	50%	17%	17%	17%
Investment alternatives	No Build		BRT1			LRT1		
			BRT2			LRT2		

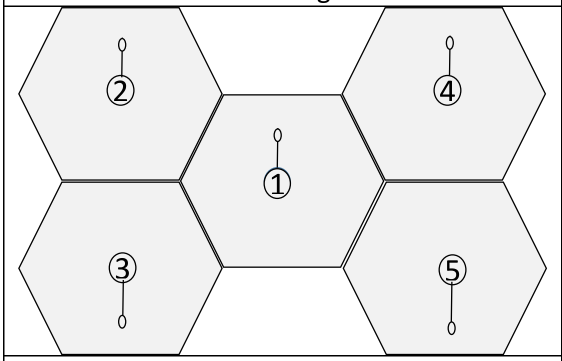
4.6.2.2. <u>Step 02 – LUT model</u>

<u>The transport model</u>

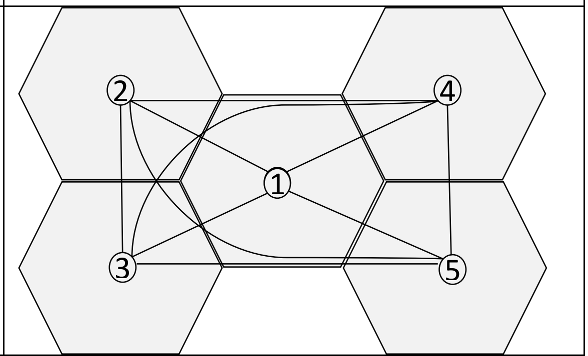
Regarding the transport model, the classical four-step model (Ortúzar and Willumsen, 2011) is applied over the generic dataset (Table 30). To estimate trip generation, population data is randomly assigned to each zone. Each household has an average of 2.2 inhabitants, and the only home typology is “single family homes”. The number of jobs varies from 20% to 70% of the population. Further on, to determine the number of trips attracted and produced the rates from the “Trip Generation Manual” (ITE, 2008) for “single family homes” and for “office parks” are applied over households and jobs, respectively. Table 29 and Table 30 present data regarding the 5 TAZs that form the area of study.

Table 29 - Investment alternatives, distances and car and walking inputs

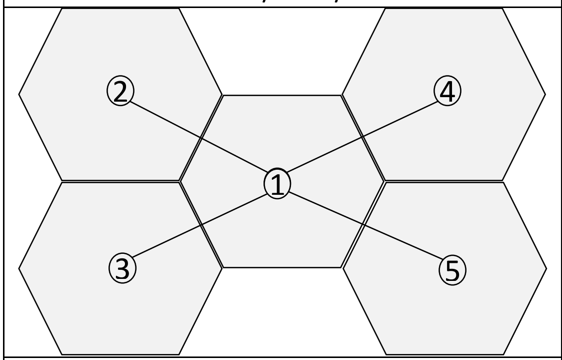
Walking



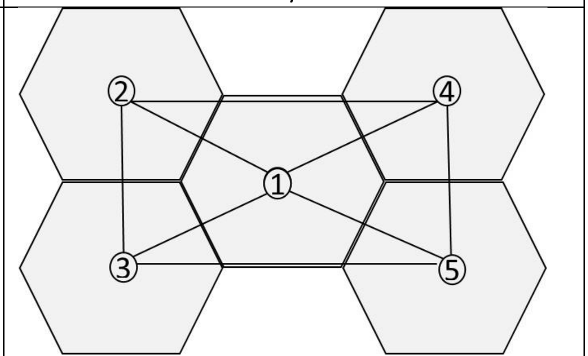
Car



No Build/BRT1/LRT1



BRT2/LRT2



Distances (km)

O/D	1	2	3	4	5
1	0.5	2.0	3.3	4.0	5.3
2	2.0	0.5	3.3	4.0	6.7
3	3.3	3.3	0.5	6.7	4.0
4	4.0	4.0	6.7	0.5	2.7
5	5.3	6.7	4.0	2.7	0.5

Car and Walking Inputs

Mode	Car	Walk
Speed (km/h)	35	5
Gas Consumption (l/100km)	7	0
Gas Cost (€/l)	1.6	0
Daily parking period (h)	8	-
Hourly parking cost (€)	0.75	

Table 30 - Population, households, jobs and trip generation data

Zone	Population	Households	Jobs	Trip generation (morning peak hour)	
				Attracted	**Produced**
1	25,000	11,364	17,500	6,320	5,423
2	15,000	6,818	7,500	3,758	2,427
3	2,500	1,136	500	618	1,338
4	5,000	2,273	2,500	1,269	1,630
5	15,000	6,818	10,500	3,815	4,962
Total	62,500	28,409	38,500	15,780	15,780

To distribute the trips generated among OD pairs, and create the Origin-Destination (O/D) Matrix, the following method is used (Bovy et al., 2006):

$$T_{ij} = \frac{e^{(\alpha * D_{ij} + \beta * W_j)} * P_i}{\sum_{j=1}^{5} e^{(\alpha * D_{ij} + \beta * W_j)}}$$

where $T_{ij}$are trips from origin "*i*" to destination "*j*"; P_i are total trips produced by origin "*i*"; D_{ij} is distance from origin "*i*" to destination "*j*"; W_j is the total number of jobs at destination "*j*"; α is 2,54E-04 and; β is 1,00E-04.

Alpha (α) and Beta (β) are estimated using the Excel Solver tool, until an acceptable level of error is reached. As this problem instance has not many zones and data to properly calibrate trip distribution, and the purpose of the model is rather testing the process, the O/D matrix (Table 31) is accepted as such.

Table 31 - O/D matrix for all modes

O/D	1	2	3	4	5	Total
1	1,524	820	571	826	2,579	6,320
2	1,073	270	275	398	1,742	3,758
3	241	89	21	125	142	618
4	583	215	210	54	207	1,269
5	2,002	1,033	261	227	292	3,815
Total	5,423	2,427	1,338	1,630	4,962	15,780

To perform mode split, it is assumed all intra-zonal trips (matrix diagonal) are made by foot and the remaining trips are either by car, bus, BRT or LRT, according to the investment alternatives. A logit model splits trip flows based on the estimated utility of each mode considering the following utility equations[17] (Eiró and Martínez, 2014):

$$\text{Car: } U = 1.024 - 0.028 * (T_t) - 0.281 * (Cost) - 0.22 * \left(T_p\right) * \left(Cost_p\right)$$

where T_t is the travel time in minutes; "$Cost$" is the fuel cost in euros, and T_p is the daily parking period in hours and "$Cost_p$" is the hourly parking cost is Euros.

$$\text{Bus: } U = \left(-0.016 * (T_t) - 0.017 * (W_t) - 0.416 * (Fare) - 0.042 * (A_t)\right) * 2.5$$

where T_t is the travel time in minutes, W_t is the waiting time in minutes, "$Fare$" is the fare price for each trip in euros, and A_t is the walking time to transit stop (in minutes).

$$\text{BRT: } U = \left(-0.016 * (T_t) - 0.017 * (W_t) - 0.416 * (Fare) - 0.042 * (A_t)\right) * 1.5$$

where T_t is the travel time in minutes, W_t is the waiting time in minutes, "$Fare$" is the fare price for each trip in euros, and A_t is the walking time to transit stop (in minutes).

$$\text{LRT: } U = -0.016 * (T_t) - 0.017 * (W_t) - 0.416 * (Fare) - 0.042 * (A_t)$$

where T_t is the travel time in minutes, W_t is the waiting time in minutes, "$Fare$" is the fare price for each trip in euros, and A_t is walking time to transit stop (in minutes). The final OD matrices for each mode and investment alternative are shown on Table 32 and Table 33. The model has an uncongested network; therefore, traffic assignment is made according to the "all-or-nothing" principle, meaning traffic follows the least-cost route. In a later section, the outputs of the LUT model are described.

The land use model

To estimate the values for the land use subcriteria, the proposed land use model was adopted (see section 4.3.2). Land use data is generated for each TAZ: area; population density; job density; average residential price (as shown on Table 34).

[17] Eiró and Martínez (2014) only provide one utility function for all public transport; hence this function has been adapted to better represent each mode.

Table 32 - O/D matrices for No Build, BRT1 and BRT2

Walking							**Car**							**Transit**							
O/D	1	2	3	4	5	Total	O/D	1	2	3	4	5	Total	O/D	1	2	3	4	5	Total	
1	1,524	0	0	0	0	1,524	1	0	749	528	769	2,424	4,470	1	0	71	43	57	155	326	
2	0	270	0	0	0	270	2	980	0	275	398	1,662	3,316	2	93	0	0	0	80	172	
3	0	0	21	0	0	21	3	223	89	0	119	142	573	3	18	0	0	6	0	24	**NB**
4	0	0	0	54	0	54	4	542	215	200	0	207	1,165	4	41	0	10	0	0	50	
5	0	0	0	0	292	292	5	1,882	986	261	227	0	3,356	5	120	47	0	0	0	167	
Total	1,524	270	21	54	292	2,161	Total	3,628	2,039	1,265	1,513	4,436	12,880	Total	271	118	52	63	234	739	
O/D	1	2	3	4	5	Total	O/D	1	2	3	4	5	Total	O/D	1	2	3	4	5	Total	
1	1,524	0	0	0	0	1,524	1	0	596	411	592	1,831	3,431	1	0	224	160	234	748	1,365	
2	0	270	0	0	0	270	2	780	0	275	398	1,238	2,691	2	293	0	0	0	504	797	
3	0	0	21	0	0	21	3	174	89	0	89	142	493	3	67	0	0	36	0	104	**BRT1**
4	0	0	0	54	0	54	4	418	215	149	0	207	989	4	165	0	61	0	0	226	
5	0	0	0	0	292	292	5	1,422	734	261	227	0	2,643	5	580	299	0	0	0	880	
Total	1,524	270	21	54	292	2,161	Total	2,794	1,634	1,097	1,306	3,418	10,248	Total	1,105	523	220	270	1,252	3,371	
O/D	1	2	3	4	5	Total	O/D	1	2	3	4	5	Total	O/D	1	2	3	4	5	Total	
1	1,524	0	0	0	0	1,524	1	0	596	411	592	1,831	3,431	1	0	224	160	234	748	1,365	
2	0	270	0	0	0	270	2	780	0	198	310	1,225	2,513	2	293	0	77	88	517	975	
3	0	0	21	0	0	21	3	174	64	0	88	102	427	3	67	25	0	37	40	170	**BRT2**
4	0	0	0	54	0	54	4	418	154	148	0	150	870	4	165	61	62	0	57	345	
5	0	0	0	0	292	292	5	1,422	726	187	164	0	2,499	5	580	307	74	63	0	1,024	
Total	1,524	270	21	54	292	2,161	Total	2,794	1,541	944	1,154	3,307	9,740	Total	1,105	616	373	422	1,363	3,879	

Table 33 - O/D matrices for LRT1 and LRT2

Walking							**Car**							**Transit**							
O/D	1	2	3	4	5	Total	O/D	1	2	3	4	5	Total	O/D	1	2	3	4	5	Total	
1	1,524	0	0	0	0	1,524	1	0	509	346	494	1,502	2,851	1	0	311	225	332	1,077	1,945	
2	0	270	0	0	0	270	2	666	0	275	398	996	2,335	2	407	0	0	0	746	1,153	
3	0	0	21	0	0	21	3	146	89	0	71	142	448	3	95	0	0	54	0	149	**LRT1**
4	0	0	0	54	0	54	4	349	215	120	0	207	891	4	234	0	90	0	0	324	
5	0	0	0	0	292	292	5	1,166	591	261	227	0	2,245	5	836	442	0	0	0	1,278	
Total	1,524	270	21	54	292	2,161	Total	2,327	1,404	1,002	1,190	2,847	8,770	Total	1,572	753	315	386	1,823	4,849	
O/D	1	2	3	4	5	Total	O/D	1	2	3	4	5	Total	O/D	1	2	3	4	5	Total	
1	1,524	0	0	0	0	1,524	1	0	509	346	494	1,502	2,851	1	0	311	225	332	1,077	1,945	
2	0	270	0	0	0	270	2	666	0	167	256	987	2,075	2	407	0	108	142	755	1,413	
3	0	0	21	0	0	21	3	146	54	0	71	85	356	3	95	35	0	54	57	241	**LRT2**
4	0	0	0	54	0	54	4	349	129	119	0	127	723	4	234	86	91	0	80	492	
5	0	0	0	0	292	292	5	1,166	585	156	139	0	2,047	5	836	448	105	88	0	1,476	
Total	1,524	270	21	54	292	2,161	Total	2,327	1,277	787	959	2,701	8,051	Total	1,572	880	530	617	1,969	5,568	

Table 34 - Land use data

Zone	Population	Jobs	% Jobs	Area (km^2)	Den_Pop (pers./km^2)	Den_Job (job/km^2)	Res. price (€/m^2)
1	25,000	17,500	41%	6.3	4,000	2,800	2,000
2	15,000	7,500	33%	7.1	2,100	1,050	1,500
3	2,500	500	17%	3.7	680	136	1,000
4	5,000	2,500	33%	2.4	2,100	1,050	750
5	15,000	10,500	41%	22.1	680	476	750

Table 34 presents land use data for the whole network. For a station area, i.e. a 1/2 -mile radius around a transit station, the data is depicted on Table 35. To estimate, for each investment alternative, the future population and the job growth within ½-mile of a transit station, growth rates (Table 24) are applied over the current the population and job figures (Table 35). With the future population and job figures, the population density is computed for each investment alternative. It is also possible to estimate the percentage of jobs for computing the entropy index. Table 36, Table 37, Table 38, Table 39 and Table 40 present the results of this procedure.

Table 35 - Land use data at a station area

Zone	Population	Jobs	% Jobs	Area (km^2)	Den_Pop (pers./km^2)	Den_Job (jobs/km^2)	Res. price (€/m^2)
1	8,137	5,696	41%	2.03	4,000	2,800	2,000
2	4,272	2,136	33%	2.03	2,100	1,050	1,500
3	1,383	277	17%	2.03	680	136	1,000
4	4,272	2,136	33%	2.03	2,100	1,050	750
5	1,383	968	41%	2.03	680	476	750

Table 36 - Population at a station area (persons)

Zone	NB	BRT1	BRT2	LRT1	LRT2
1	8,137	8,950	8,950	8,706	8,706
2	4,272	4,699	4,699	4,571	4,571
3	1,383	1,522	1,522	1,480	1,480
4	4,272	4,699	4,699	4,571	4,571
5	1,383	1,522	1,522	1,480	1,480

Table 37 - Jobs at a station area (jobs)

Zone	NB	BRT1	BRT2	LRT1	LRT2
1	5,696	8,544	8,544	6,664	6,664
2	2,136	3,204	3,204	2,499	2,499
3	277	415	415	324	324
4	2,136	3,204	3,204	2,499	2,499
5	968	1,452	1,452	1,133	1,133

Table 38 - Population density at a station area (persons/km²)

Zone	NB	BRT1	BRT2	LRT1	LRT2
1	4,000	4,400	4,400	4,280	4,280
2	2,100	2,310	2,310	2,247	2,247
3	680	748	748	728	728
4	2,100	2,310	2,310	2,247	2,247
5	680	748	748	728	728

Table 39 - Percentage of jobs at a station area

Zone	NB	BRT1	BRT2	LRT1	LRT2
1	41%	49%	49%	43%	43%
2	33%	41%	41%	35%	35%
3	17%	21%	21%	18%	18%
4	33%	41%	41%	35%	35%
5	41%	49%	49%	43%	43%

Table 40 - Entropy index at a station area

Zone	NB	BRT1	BRT2	LRT1	LRT2
1	98%	100%	100%	99%	99%
2	92%	97%	97%	94%	94%
3	65%	75%	75%	68%	68%
4	92%	97%	97%	94%	94%
5	98%	100%	100%	99%	99%

To estimate, for each investment alternative, residential property prices within ½-mile of a transit station, growth rates (Table 24) are applied over current residential property price figures (Table 35) - see Table 41.

Table 41 - Residential property prices at a station area

Zone	NB	BRT1	BRT2	LRT1	LRT2
1	2,000	2,152	2,152	2,060	2,060
2	1,500	1,614	1,614	1,545	1,545
3	1,000	1,076	1,076	1,030	1,030
4	750	807	807	773	773
5	750	807	807	773	773

Finally, accessibility is estimated with an isochrone-based measure (Accessibility Observatory, 2014). To estimate accessibility, total current jobs must be computed for each investment alternative, as depicted on Table 42. Accessibility is based on current job data, instead of future jobs, as It is a conservative approach and avoids potential uncertainty from job forecasting to pass along to accessibility estimation.

Table 42 - Current Job data

Zone	NB	BRT1	BRT2	LRT1	LRT2
1	17,500	17,500	17,500	17,500	17,500
2	7,500	7,500	7,500	7,500	7,500
3	500	500	500	500	500
4	2,500	2,500	2,500	2,500	2,500
5	10,500	10,500	10,500	10,500	10,500
Total	38,500	38,500	38,500	38,500	38,500

The transit travel times needed to reach each zone from the remainder zones, for each investment alternative, is depicted in Table 43, Table 44, Table 45, Table 46 and Table 47. For each O/D pair, if transit travel time is equal or below 60 minutes, all jobs in the destination TAZ are considered, otherwise none. Table 48, Table 49, Table 50, Table 51 and Table 52 present the final accessibility calculations.

Table 43 – Transit travel time skims for No Build

O/D	1	2	3	4	5
1	Walk[18]	22	28	31	37
2	22	Walk	N S[19]	N S	47
3	28	N S	Walk	47	N S
4	31	N S	47	Walk	N S
5	37	47	N S	N S	Walk

Table 44 - Transit travel time skims for BRT1

O/D	1	2	3	4	5
1	Walk	14	17	18	21
2	14	Walk	N S	N S	26
3	17	N S	Walk	26	N S
4	18	N S	26	Walk	N S
5	21	26	N S	N S	Walk

Table 45 - Transit travel time skims for BRT2

O/D	1	2	3	4	5
1	Walk	14	17	18	21
2	14	Walk	17	32	24
3	17	17	Walk	24	18
4	18	18	24	Walk	15
5	21	24	18	15	Walk

[18] Walk: although intrazonal trips are restricted to walking, they are considered as having transit travel times below or equal 60 minutes.

[19] NS: no transit service connecting the O/D pair.

Table 46 - Transit travel time skims for LRT1

O/D	1	2	3	4	5
1	Walk	13	16	17	20
2	13	Walk	N S	N S	24
3	16	N S	Walk	24	N S
4	17	N S	24	Walk	N S
5	20	24	N S	N S	Walk

Table 47 - Transit travel time skims for LRT2

O/D	1	2	3	4	5
1	Walk	13	16	17	20
2	13	Walk	16	29	22
3	16	16	Walk	22	17
4	17	17	22	Walk	14
5	20	22	17	14	Walk

Table 48 - Accessibility for No Build

O/D	1	2	3	4	5	Accessible Jobs	Total Jobs	%
1	17,500	7,500	500	2,500	10,500	38,500		100%
2	17,500	7,500	-	-	10,500	35,500		92%
3	17,500	-	500	2,500	-	20,500	38,500	53%
4	17,500	-	500	2,500	-	20,500		53%
5	17,500	7,500	-	-	10,500	35,500		92%
Accessibility (mean)								78%

Table 49 - Accessibility for BRT1

O/D	1	2	3	4	5	Accessible Jobs	Total Jobs	%
1	17,500	7,500	500	2,500	10,500	38,500		100%
2	17,500	7,500	-	-	10,500	35,500		92%
3	17,500	-	500	2,500	-	20,500	38,500	53%
4	17,500	-	500	2,500	-	20,500		53%
5	17,500	7,500	-	-	10,500	35,500		92%
Accessibility (mean)								78%

Table 50 - Accessibility for BRT2

O/D	1	2	3	4	5	Accessible Jobs	Total Jobs	%
1	17,500	7,500	500	2,500	10,500	38,500		100%
2	17,500	7,500	500	2,500	10,500	38,500		100%
3	17,500	7,500	500	2,500	10,500	38,500	38,500	100%
4	17,500	7,500	500	2,500	10,500	38,500		100%
5	17,500	7,500	500	2,500	10,500	38,500		100%
Accessibility (mean)								100%

Table 51 – Accessibility for LRT1

O/D	1	2	3	4	5	Accessible Jobs	Total Jobs	%
1	17,500	7,500	500	2,500	10,500	38,500	38,500	100%
2	17,500	7,500	-	-	10,500	35,500		92%
3	17,500	-	500	2,500	-	20,500		53%
4	17,500	-	500	2,500	-	20,500		53%
5	17,500	7,500	-	-	10,500	35,500		92%
Accessibility (mean)								78%

Table 52 - Accessibility for LRT2

O/D	1	2	3	4	5	Accessible Jobs	Total Jobs	%
1	17,500	7,500	500	2,500	10,500	38,500	38,500	100%
2	17,500	7,500	500	2,500	10,500	38,500		100%
3	17,500	7,500	500	2,500	10,500	38,500		100%
4	17,500	7,500	500	2,500	10,500	38,500		100%
5	17,500	7,500	500	2,500	10,500	38,500		100%
Accessibility (mean)								100%

4.6.2.3. Step 03 – Capacity threshold check

After step 02, a capacity check is performed. The load factor of any public transport vehicle should not exceed 90%. If this is not the case, we return to step 01, changing the parameters that affect the load factor (for instance, the frequency and capacity of vehicles). In the example under study, all alternatives respect the established threshold – Table 53, Table 54, Table 55 and Table 56 depict the procedure.

Table 53 - Capacity check for lines NB1 and NB2

NB1	**In**	**Out**	**Vol (1hr)**	**Vehicle capacity (1hr)**	**Load factor (%)**	**NB2**	**In**	**Out**	**Vol (1hr)**	**Vehicle capacity (1hr)**	**Load factor (%)**
2	172	0	172	260	66%	3	24	0	24	260	9%
1	155	93	234	260	90%	1	57	18	63	260	24%
5	0	234	0			4	0	63	0		
5	167	0	167	260	64%	4	50	0	50	260	19%
1	71	120	118	260	45%	1	43	41	52	260	20%
2	0	118	0			3	0	52	0		

Table 54 - Capacity check for lines A and B

A	**In**	**Out**	**Vol (1hr)**	**Vehicle capacity (1hr)**	**Load factor (%)**	**B**	**In**	**Out**	**Vol (1hr)**	**Vehicle capacity (1hr)**	**Load factor (%)**
2	797	0	797	1,500	53%	3	104	0	104	1,500	7%
1	748	293	1,252	1,500	83%	1	234	67	270	1,500	18%
5	0	1 252	0			4	0	270	0		
5	880	0	880	1,500	59%	4	226	0	226	1,500	15%
1	224	580	523	1,500	35%	1	160	165	220	1,500	15%
2	0	523	0			3	0	220	0		

Table 55 - Capacity check for lines D and E

D	In	Out	Vol (1hr)	Vehicle capacity (1hr)	Load factor (%)	E	In	Out	Vol (1hr)	Vehicle capacity (1hr)	Load factor (%)
2	1,153	0	1,153	2,400	48%	3	149	0	149	2,400	6%
1	1,077	407	1,823	2,400	76%	1	332	95	386	2,400	16%
5	0	1,823	0			4	0	386	0		
5	1,278	0	1,278	2,400	53%	4	324	0	324	2,400	14%
1	311	836	753	2,400	31%	1	225	234	315	2,400	13%
2	0	753	0			3	0	315	0		

Table 56 - Capacity check for lines C and F

C	In	Out	Vol (1hr)	Vehicle capacity (1hr)	Load factor (%)	F	In	Out	Vol (1hr)	Vehicle capacity (1hr)	Load factor (%)
2	594	0	594	1,500	40%	2	863	0	863	2,400	36%
3	77	77	595	1,500	40%	3	111	108	866	2,400	36%
5	370	558	407	1,500	27%	5	535	812	590	2,400	25%
4	61	100	368	1,500	25%	4	86	142	534	2,400	22%
2	0	368	0			2	0	534	0		
2	88	0	88	1,500	6%	2	142	0	142	2,400	6%
4	120	88	120	1,500	8%	4	171	142	171	2,400	7%
5	74	57	136	1,500	9%	5	105	80	196	2,400	8%
3	25	136	25	1,500	2%	3	35	196	35	2,400	1%
2	0	25	0			2	0	35	0		

4.6.2.4. Step 04 – Outputs

To estimate costs, the same sample of projects used to define market values (FTA, 2016a) was here consulted. The median BRT and LRT capital costs per km of US$ 6.1 M/km and US$ 77.5 M/km, respectively, are adopted for the investment alternatives. For the “No Build” alternative, capital costs are assumed as zero, as no major investment is done on the system. The median BRT and LRT operating costs per year per km of US$ 0.2 M/year/km and US$ 1.0 M/year/km, respectively, are adopted for the investment alternatives. For the “No Build” alternative, operating costs are US$ 0.16 M/year/km, resulting from the division of the US$ 202 M (MBTA’s bus budgeted operating costs for FY2016 (MBTA, 2015)) per about 1,200km (total MBTA’s bus network length). Table 57 presents capital and operating costs for each investment alternative.

Revenues are defined as total daily linked trips per km, a proxy for farebox revenues. To estimate this value, peak hour transit OD matrices are multiplied by 2, to count boardings and alightings, with a conversion factor, from peak hour trips to daily (24-hour) trips, of 7.14, drawn from a recent urban mobility survey done in Lisbon Metropolitan Area (MIT Portugal, 2008). Then, total daily trips are divided by the project length.

Transit travel times are estimated as the average transit travel times. Waiting (half of frequency) and pedestrian access time to the transit stops are considered. Mode share is the share of walking and transit trips for each investment alternative and, to avoid further unnecessary complexity on modeling, transfers are not allowed in this network. To estimate the emissions, the same sample of projects used to define market values (FTA, 2010) is here consulted. The median Bus/BRT and LRT CO_2 emissions of 181 gCO_2/pax.km and 119 gCO_2/pax.km, respectively, are adopted for the investment alternatives. Table 57 depicts the computed or estimated values.

Real estate, density, mixed-use and accessibility are the averages of residential property prices per square meter per zone, population densities per zone, entropies of population and jobs per zone and accessibilities per zone, respectively for each investment alternative. Table 57 depicts the resulting values.

Table 57 - LUT model outputs

Criterion	Subcriterion	NB	BRT1	BRT2	LRT1	LRT2
Finance	Capital costs (M US$/km)	0	6.1	6.1	77.5	77.5
	Operating costs (M US$/year/km)	0.16	0.2	0.2	1.03	1.03
	Revenues (trips/day/km)	720	3,283	1,933	4,723	2,775
Transport	Travel time (minutes)	40	20.6	20.1	19.2	18.8
	Mode share (%)	18%	35%	38%	44%	49%
	Transfers	0	0	0	0	0
	CO_2 emissions (g/pax.km)	181	181	181	119	119
Land use	Real estate (€/m^2)	1,200	1,291	1,291	1,236	1,236
	Density (Pop/km^2)	1,912	2,103	2,103	2,046	2,046
	Mixed-use (Entropy)	89%	94%	94%	91%	91 %
	Accessibility (%)	78%	78%	100%	78%	100%

4.6.2.5. *Step 05 – Value functions*

The development of value functions for each alternative requires the normalization of the outputs to a common scale. As presented in 4.4.1, a procedure was designed for this purpose, considering reference values from recent market figures, as observed in BRT and LRT projects in the US (FTA, 2016a) and on general transport and land use data from US metropolitan areas (Accessibility Observatory, 2014; FHA, 2009; FTA, 2010; U. S. Census Bureau, 2014; Zillow, 2016). A linear behavior is assumed, this meaning the decision-maker, for a given criterion, values equally the same "amount" of change whatever the absolute figures are – e.g. a capital cost reduction from 35 to 5 is equal to a reduction from 65 to 35 (this making the situations indifferent). Finally, the value functions are additive – the final score of an alternative is a weighted sum of its criteria and subcriteria values, with "weights" obtained from the experts' priority profiles (Table 58 depicts the normalized values). Although market values are limited to zero being the worst and one being the best outcomes, values might under or overpass those limits.

Table 58 - Normalized values

Criterion	Subcriterion	NB	BRT1	BRT2	LRT1	LRT2		Market Values	
								Best	Worst
Finance	Capital costs (M US$/km)	1.08	0.98	0.98	-0.21	-0.21		5	65
	Operating costs (M US$/year/km)	1.05	0.99	0.99	-0.03	-0.03		0.2	1
	Revenues (trips/day/km)	-0.14	0.32	0.08	0.59	0.23		7,000	1,500
Transport	Travel time (minutes)	-0.50	0.47	0.49	0.54	0.56		10	30
	Mode share (%)	1.34	3.01	3.33	3.94	4.40		15	5
	Transfers	1.00	1.00	1.00	1.00	1.00		0	3
	CO_2 emissions (g/pax.km)	0.19	0.19	0.19	0.81	0.81		100	200
Land use	Real estate (€/m^2)	0.19	0.24	0.24	0.21	0.21		2,622	874
	Density (Pop/km^2)	0.27	0.40	0.40	0.36	0.36		3,000	1,500
	Mixed-use (Entropy)	0.94	1.20	1.20	1.03	1.03		90	70
	Accessibility (%)	7.32	7.32	9.50	7.32	9.50		15	5

The normalized values above 1 or below 0 could be removed with new market values that could cover all values of the investment alternatives (e.g. for the capital costs subcriterion, the "worst" market value would have to be equal or higher than the highest capital cost estimated, and the "best" market value would have to be equal or lower than the lowest capital cost estimated). However, changing the market values would require changing the weights in the expert's priority profile accordingly as well, so the distances between the final scores (i.e. the results of the value functions – see Table 60) would remain the same – a linear transformation would occur.

When the experts answered the survey, they explicitly compared variations (from the worst to the best market value, for each subcriterion) considering the market values adopted in this work, e.g. a decrease from 65 to 5M US$/km in capital costs, hence their answers strictly reflect *that interval and not any other interval.* Therefore, with new market values, new weights would have to be computed. This procedure would eliminate those somewhat strange normalized values (e.g. "-0.21" for LRT capital costs or "9.50" for BRT accessibility – see Table 58) and change the values of the final scores, however it would not the choice nor the ranking.

4.6.2.6. <u>Step 06 – Expert's priority profiles</u>

As described in 4.4.2, the same market values were used in a survey based on the AHP method. This survey was answered by 17 public transport experts from Brazil, Canada, Germany, the Netherlands, Portugal and the USA. The survey uses the hierarchy proposed in step 04 and, based on the experts' responses, assigns a "weight" to each of the subcriteria and to each of the three criteria.

Responses are treated in a "standard" worksheet (Goepel, 2013), where consistency ratios (CR) and weights are computed. The CRs present different values, and some exceeded the threshold suggested by Saaty – CR <0.1. Responses with CR>0.2 are slightly adjusted until reaching a CR<0.2. The final priority profile is shown in Table 59.

Table 59 – Experts' priority profile

Criteria	**Subcriteria**	**Final weights**	**Equivalent weights**	**Order of priority**
Finance		27.3%		
	Capital cost	21.7%	5.9%	9th
	Operating cost	33.0%	9.0%	4th
	Revenues	45.3%	12.4%	2nd
Transport		52.4%		
	Travel time	42.7%	22.4%	1st
	Mode share	23.5%	12.3%	3rd
	Transfers	17.0%	8.9%	5th
	Emissions	16.8%	8.8%	6th
Land use		20.2%		
	Real estate	18.1%	3.7%	10th
	Density	31.3%	6.3%	8th
	Mixed-use	15.7%	3.2%	11th
	Accessibility	34.9%	7.1%	7th

4.6.2.7. Step 07 – Choice and ranking

With the weights on the value functions, each alternative is assigned a score, leading to a ranking of the alternatives. In the example, the final ranking is: LRT2, BRT2, LRT1, BRT1, and No Build.

Table 60 depicts the ranking and the scores (obtained by a weighted sum of finance, transport and land use criteria scores). The score of each criterion is computed by considering its subcriteria and associated weights.

Table 60 - Choice and ranking

Ranking	Investment alternative	Criteria scores			Final score
		Finance	Transport	Land use	
1st	LRT2	0.01	0.83	0.73	1.57
2nd	BRT2	0.16	0.63	0.74	1.53
3rd	LRT1	0.06	0.77	0.58	1.40
4th	BRT1	0.19	0.58	0.59	1.36
5th	No Build	0.14	0.16	0.57	0.87

4.6.2.8. Step 08 – Sensitivity analysis

Uncertainty in the modeling process and inputs

To perform sensitivity analysis, several uncertainty scenarios were tested: a first group of global scenarios, affecting all investment alternatives equally; and two other groups of more specific scenarios, with specific probabilities assigned to each investment alternative. Finally, a different approach was tested where a multi-objective problem was designed to find optimal alternatives. Overall, all these procedures try to answer the question:

What changes in the modeling process and inputs would lead to changes in the ranking of the alternatives?

Some outputs are frequently over or underestimated. For instance, after analyzing results from before-and-after reports of New Starts and Small Starts Projects issued annually by FTA from 2007 to 2015 (FTA, 2016d), LRT capital costs and operating costs are underestimated in 36% and 50% of the projects, respectively; and LRT ridership levels are overestimated in 40% of the projects.

According to the experts' weight profile (Table 59), travel time (22.4%), revenues (12.4%), mode share (12.3%) and operating costs (9.0%) together sum up to almost 60% of the total weight, thus having a major impact on the final choice and on the ranking of the alternatives. This information aids on the design of realistic "uncertainty" scenarios. In a real-life situation, the decision-maker, the analysts and the experts would help assembling such scenarios and their associated probabilities. The scenarios were defined as follows:

- Pessimistic "A" (PA): For all investment alternatives, operating costs, travel times and revenues worsen by 30%. Probability: 20%
- Pessimistic "B" (PB): For all investment alternatives, operating costs, travel times and revenues worsen by 10%. Probability: 45%

- Neutral (N): scenario for current outcome. Probability: 20%.
- Optimistic “D” (OD): For all investment alternatives, operating costs, travel times and revenues improve by 10%. Probability: 10%
- Optimistic “E” (OE): For all investment alternatives, operating costs, travel times and revenues improve by 30%. Probability: 5%

Table 61, Table 62 and Figure 30 depict the inputs and results from this set of scenarios. Results from the scenarios tested do not change the final ranking, mainly because they act over all investment alternatives, thus degrading or upgrading all of them. This exercise does, however, give some understanding on the behavior of each alternative under some uncertainty. Scenarios such as the ones proposed here are normally derived from more global concerns, often expressed by stakeholders involved in the decision-making process, about escalating costs and degrading system performance.

Table 61 - Inputs to the first set of scenarios

Scenarios	**Operating costs (M.US$/year/km)**			**Revenues (trips/day/km)**					**Travel time (min)**				
	NB	**BRTs**	**LRTs**	**NB**	**BRT1**	**BRT2**	**LRT1**	**LRT2**	**NB**	**BRT1**	**BRT2**	**LRT1**	**LRT2**
PA	0.2	0.27	0.27	504	2,298	1,353	3,306	1,942	52	26.7	26.2	24.9	24.4
PB	0.17	0.23	0.23	648	2,955	1,740	4,251	2,497	44	22.6	22.1	21.1	20.7
N	0.16	0.2	0.2	720	3,283	1,933	4,723	2,775	40	20.6	20.1	19.2	18.8
OD	0.14	0.18	0.18	792	3,612	2,126	5,196	3,052	36	18.5	18.1	17.3	16.9
OE	0.11	0.14	0.14	936	4,268	2,513	6,140	3,607	28	14.4	14.1	13.4	13.2

Table 62 - Results from the first set of scenarios

Scenarios		**NB**	**BRT1**	**BRT2**	**LRT1**	**LRT2**
PA (p =20%)	Scores	0.75	1.29	1.46	1.29	1,48
	Ranking	5th	4th	2nd	3rd	1st
PB (p = 45%)	Scores	0.84	1.35	1.52	1.38	1,56
	Ranking	5th	4th	2nd	3rd	1st
N (p = 20%)	Scores	0.89	1.38	1.55	1.43	1,6
	Ranking	5th	4th	2nd	3rd	1st
OD (p = 10%)	Scores	0.94	1.42	1.58	1.47	1,63
	Ranking	5th	4th	2nd	3rd	1st
OE (p = 5%)	Scores	1.04	1.48	1.64	1.56	1,71
	Ranking	5th	4th	2nd	3rd	1st
Expected score		0.85	1.36	1.53	1.39	1.56
Worst score		0.75	1.29	1.46	1.29	1.48

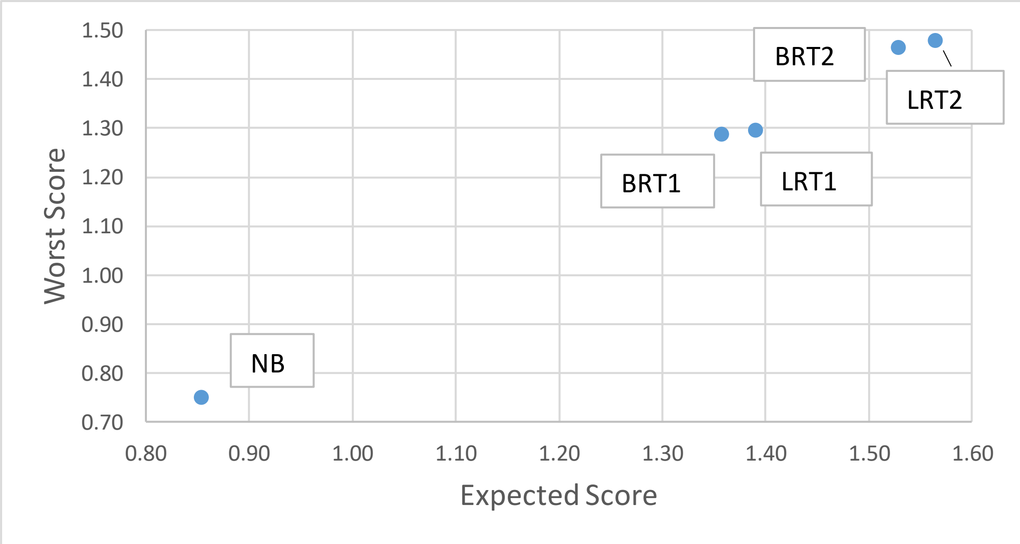


Figure 30 - Results from the first set of scenarios

Another set of scenarios were tested using the 2016 MBTA reliability data (MBTA, 2017): 40%, 17% and 29% of MBTA buses, BRTs and LRTs were not on time, respectively. With that information, it is possible to build 2 travel time uncertainty scenarios (Table 63, Table 64 and Figure 31). In the absence of better data, a typical delay could take up to 5 minutes. In these two scenarios, LRT2 remains the chosen alternative.

Table 63 - Inputs of the reliability set of scenarios

Delay scenario	NB (p=40%)	BRT1 (p=17%)	BRT2 (p=17%)	LRT1 (p=29%)	LRT2 (p=29%)
	45.0 min.	25.6 min.	25.2 min.	24.2 min.	23.8 min.
Neutral scenario	NB (p=60%)	BRT1 (p=83%)	BRT2 (p=83%)	LRT1 (p=71%)	LRT2 (p=71%)
	40.0 min.	20.6 min.	20.1 min.	19.2 min.	18.8 min.

Table 64 - Results from the reliability set of scenarios

Scenarios		**NB**	**BRT1**	**BRT2**	**LRT1**	**LRT2**
Delay	Scores	0.84	1.33	1.50	1.37	1.54
	Ranking	5th	4th	2nd	3rd	1st
Neutral	Scores	0.89	1.38	1.55	1.43	1.60
	Ranking	5th	4th	2nd	3rd	1st
Expected score		0.88	0.87	1.37	1.54	1.41
Worst score		0.85	0.85	1.38	1.61	1.45

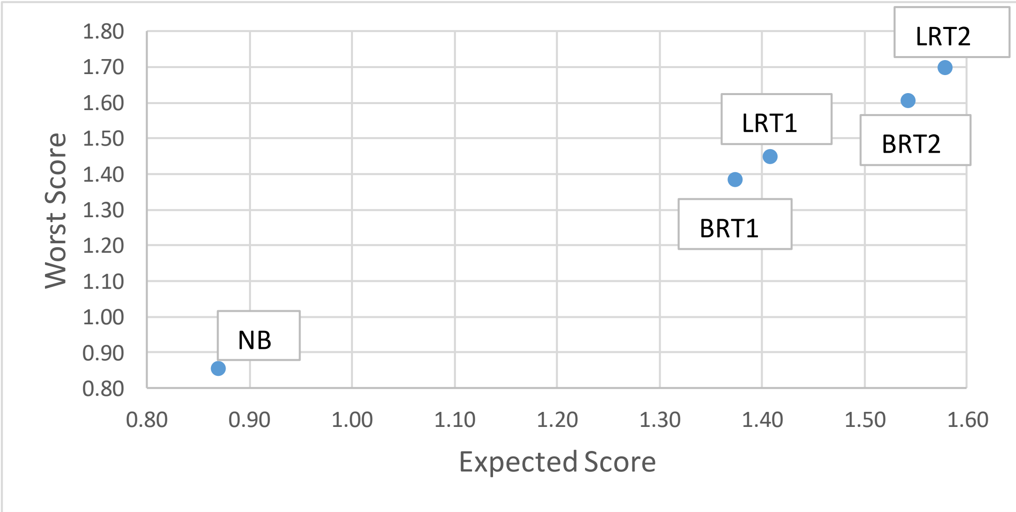


Figure 31 - Results from the reliability set of scenarios

A fundamental issue on the BRT vs LRT debate is the so-called *sense of permanence*. As discussed in chapter 2, some authors acknowledge that rail systems (LRT) might impact more real estate and urban environment than road systems (BRT).

Higgins and Kanaroglou (2016), reviewing forty years of modeling rapid transit and land value uplift in North America, show that:

- LRT's residential property price impacts vary substantially, with about 50% probability of being positive; 25% probability of being none and 25% probability of being negative;
- For BRT, it is about 40% probability of being positive; 40% probability of being none and 20% probability of being negative.

With these information, three real estate uncertainty scenarios are assembled (Table 65 and Table 66). For Pessimistic F (PF) scenario, a negative property price impact of 1.5% is assigned for LRTs and a negative property price impact of 3% is assigned for BRTs (these are the lowest negative impacts reported by Higgins and Kanaroglou (2016)). For Pessimistic G (PG) scenario, property value impacts are none and for the Neutral (N) scenario, property value impacts are the current impacts.

From these scenarios, the scores and the ranking remain the same, with LRT2 as the chosen alternative. As presented on Table 59, after mixed-use, real estate is the least important subcriterion according to the expert's priority profile, hence changing its values will not have significant impact on final outcomes.

Table 65 - Inputs to the real estate set of scenarios

Pessimistic F (PF) scenario	NB (p=0%)	BRT1 (p=20%)	BRT2 (p=20%)	LRT1 (p=24.5%)	LRT2 (p=24.5%)
	1,200 €/m²	1,164 €/m²	1,164 €/m²	1,182 €/m²	1,182 €/m²
Pessimistic G (PG) scenario	NB (p=0%)	BRT1 (p=40%)	BRT2 (p=40%)	LRT1 (p=24.6%)	LRT2 (p=24.6%)
	1,200 €/m²	1,200 €/m²	1,200 €/m²	1,200 €/m²	1,200 €/m²
Neutral (N) scenario	NB (p=100%)	BRT1 (p=40%)	BRT2 (p=40%)	LRT1 (p=50.9%)	LRT2 (p=50.9%)
	1,200 €/m²	1,291 €/m²	1,291 €/m²	1,236 €/m²	1,236 €/m²

Table 66 - Results from the real estate set of scenarios

Scenarios		**NB**	**BRT1**	**BRT2**	**LRT1**	**LRT2**
PF	Scores	0.89	1.38	1.55	1.42	1,59
	Ranking	5th	4th	2nd	3rd	1st
PG	Scores	0.89	1.38	1.55	1.42	1,60
	Ranking	5th	4th	2nd	3rd	1st
N	Scores	0.89	1.38	1.55	1.43	1,60
	Ranking	5th	4th	2nd	3rd	1st
Expected score		0.89	1.38	1.55	1.42	1.60
Worst score		0.89	1.38	1.55	1.42	1.59

Finally, we have performed a sensitivity analysis on travel times and revenues. Along with headway, one model input that markedly affects these two subcriteria is station spacing (Figure 32 and Figure 33). For this case study, the station spacing producing the lowest travel time and highest revenues should be optimal (Figure 34, Figure 35, Figure 36, Figure 37 and Figure 38).

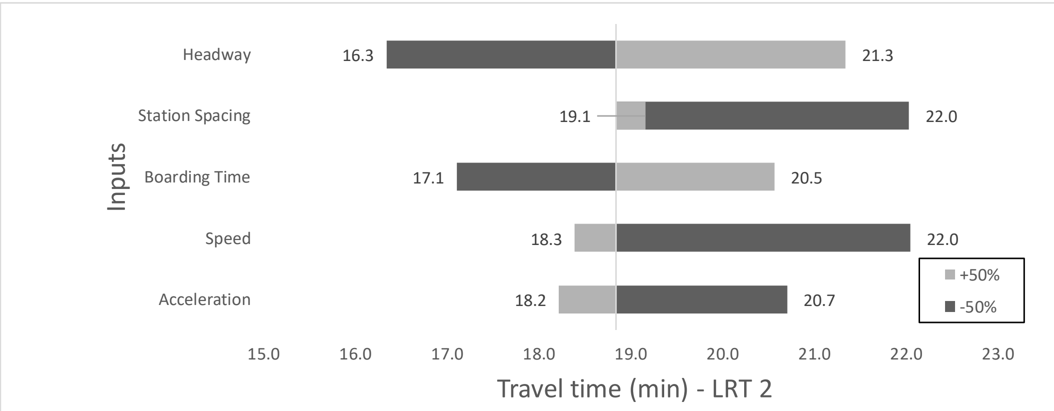


Figure 32 - Tornado plot for travel times

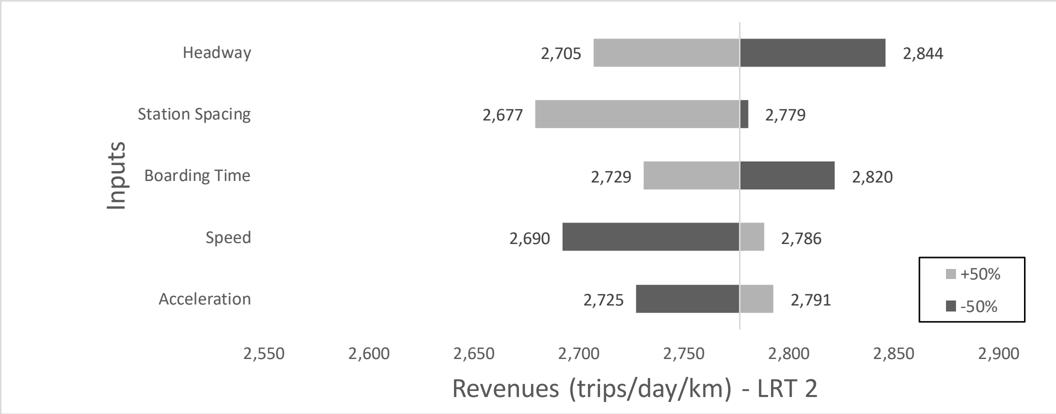


Figure 33 - Tornado plot for revenues

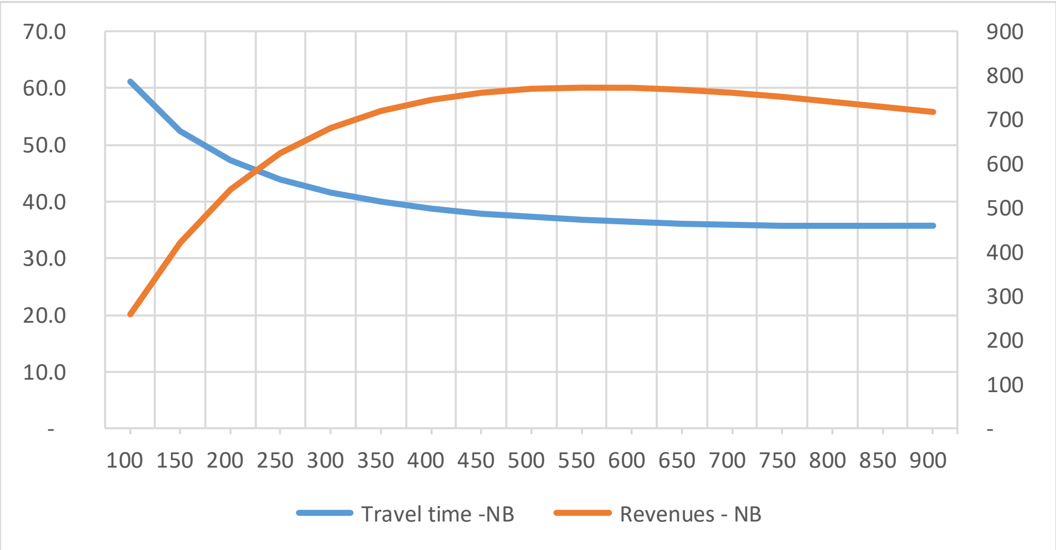


Figure 34 - Travel time and revenues for No Build

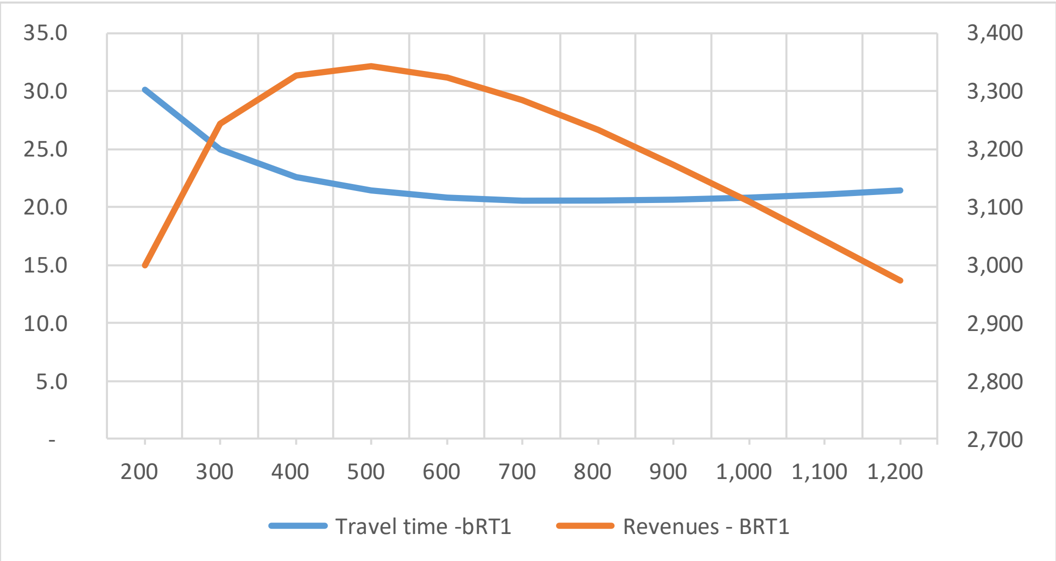


Figure 35 - Travel time and revenues for BRT1

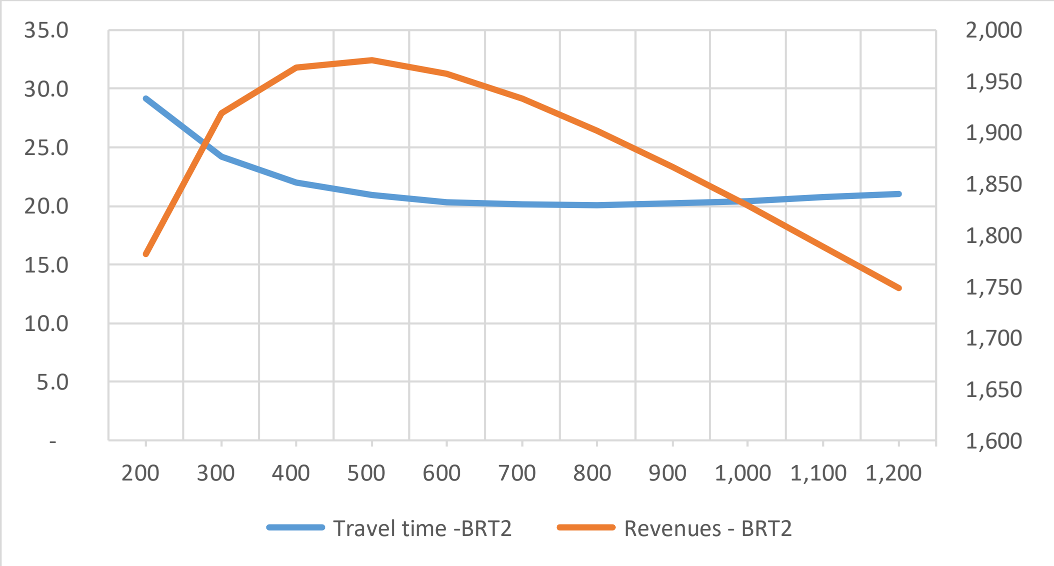


Figure 36 - Travel time and revenues for BRT2

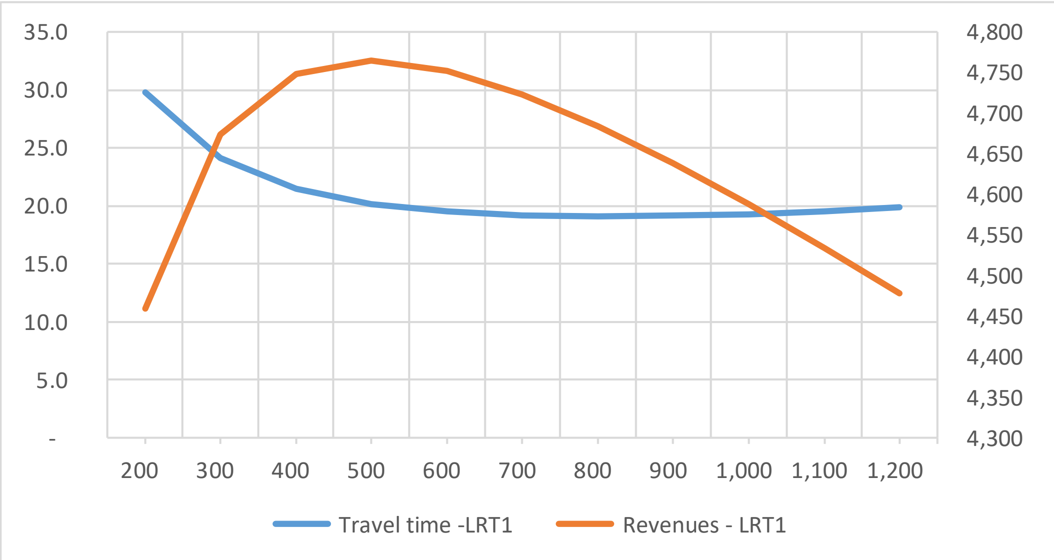


Figure 37 - Travel time and revenues for LRT1

From these graphs, the No Build alternative yields the highest revenues and lowest travel times at a station spacing[20] of 650m, BRT2 at 600m and BRT1, LRT1 and LRT2 at 700m. After adopting these figures as model inputs, we get the final scores and ranking depicted in Table 67. Although the

[20] These figures should not be regarded as guidance or best practice for future projects. Defining station spacing involves more than just travel time and revenues, for instance, population density and location of points of interests.

scores change slightly, the ranking remains as before. From all scenarios tested, none was able to change the final outcome, thus LRT2 remains as the chosen alternative.

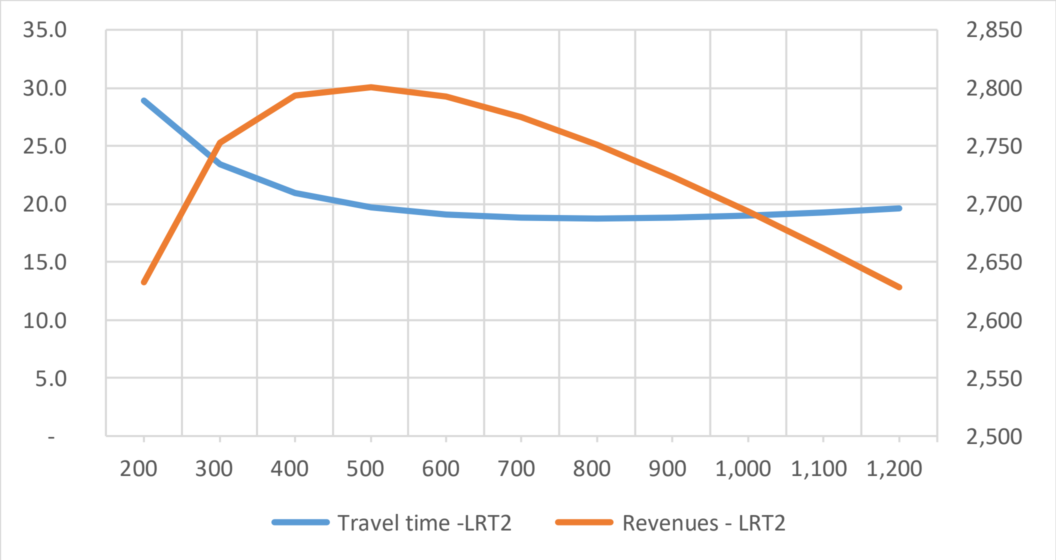


Figure 38 - Travel time and revenues for LRT2

Table 67 - Results from the optimization scenario

Ranking	Investment Alternative	Criteria scores			Final Score
		Finance	Transport	Land use	
1st	LRT2	0.01	0.83	0.75	1.60
2nd	BRT2	0.16	0.63	0.77	1.55
3rd	LRT1	0.06	0.77	0.60	1.43
4th	BRT1	0.19	0.58	0.61	1.38
5th	No Build	0.14	0.21	0.59	0.94

<u>Normalization</u>

How does the normalization process influence the ranking?

Within the normalization process, it seems natural to make experiments by changing adopting a non-linear normalization scale.

A possible analysis is changing to a non-linear normalization scale. One common procedure is to define the normalization function, with the help of the decision-maker. The decision-maker might not value equally the changes in subcriteria, e.g. he might value more a capital cost reduction from 35 to 5 than from 65 to 35, although both reductions are 30. Such behavior is easily translated into an exponential function. Figure 39 presents three functions for the capital cost subcriterion.

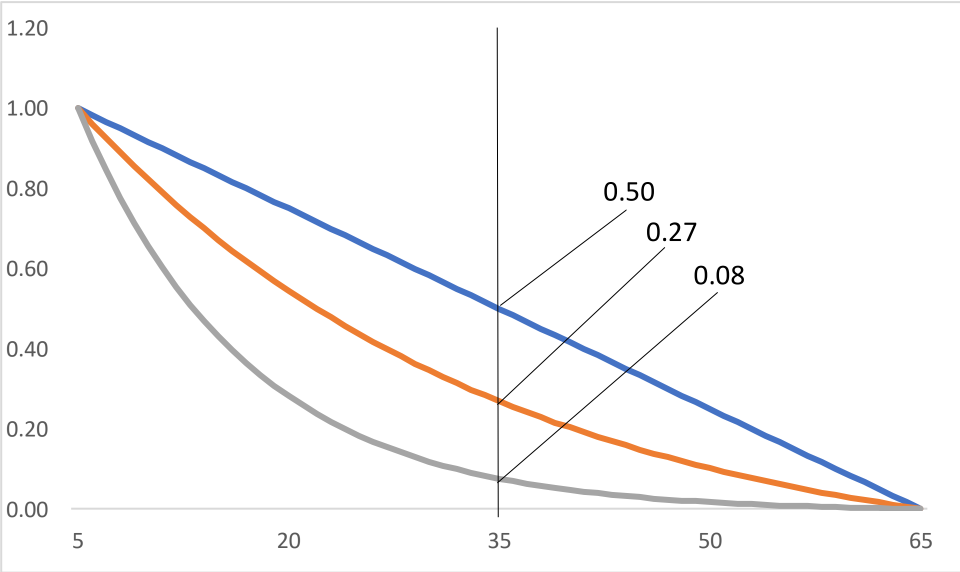


Figure 39 - Normalization functions

In a linear function, there is no a preference towards better values, as it is the case of exponential functions. The two exponential functions reflect a preference towards smaller values, which in this case are cheaper alternatives: mild preference for the red alternative; strong preference for the gray alternative. The exponential normalization tends to value more improvements on subcriteria and therefore values closer or above the upper market value limits will highly dictate the final choice. As no expert was consulted on this issue, we decided to not analyze different normalization processes.

Priority profiles

How does the priority profile influence the ranking?

Along with the normalization process, another substantial source of variability is the priority profile. In this research, several experts are surveyed to develop the priority profile, thus generating several different opinions and preferences on the criteria and subcriteria. To assemble the final weight profile, the AHP eigenvector was chosen. Other possible weight profiles consist in the average or the mode of all expert answers. Table 68 and Table 69 present these cases and final scores.

Although there are substantial changes on the weights, leading to a more balanced profile, the ranking remains the same in the first case, but changes occur in the second case, with BRT2 in the first place, followed by LRT2, BRT1, LRT1 and No Build. Other plausible cases for the priority profile will reflect exogenous market or policy pressures, for instance, a *transit user* case (Table 70), a *financial-constrained* case (Table 71) an *urban-friendly* case (Table 72).

Table 68 - Average priority profile case

Criteria/Alternatives	Weights		NB	BRT1	BRT2	LRT1	LRT2
	Final	Equivalent					
Finance	28.5%		0.2	0.2	0.2	0.1	0.0
Capital cost	23.8%	6.8%	0.3	0.2	0.2	0.0	0.0
Operating cost	33.3%	9.5%	0.4	0.3	0.3	0.0	0.0
Revenues	42.9%	12.2%	-0.1	0.1	0.0	0.3	0.1
Transport	50.2%		0.2	0.6	0.6	0.8	0.8
Travel time	39.7%	19.9%	-0.2	0.2	0.2	0.2	0.2
Mode share	24.4%	12.2%	0.3	0.7	0.8	1.0	1.1
Transfers per trip	18.1%	9.1%	0.2	0.2	0.2	0.2	0.2
Emissions	17.8%	8.9%	0.0	0.0	0.0	0.1	0.1
Land use	21.3%		0.5	0.6	0.7	0.6	0.7
Real estate	21.2%	4.5%	0.0	0.1	0.1	0.0	0.0
Mixed-use	17.6%	3.7%	0.1	0.1	0.1	0.1	0.1
Density	30.5%	6.5%	0.2	0.2	0.2	0.2	0.2
Accessibility	30.8%	6.6%	2.3	2.3	2.9	2.3	2.9
Score			0.87	1.33	1.49	1.36	1.52
Ranking			5th	4th	2nd	3rd	1st

Table 69 - Mode priority profile case

Criteria/Alternatives	Weights		NB	BRT1	BRT2	LRT1	LRT2
	Final	Equivalent					
Finance	29.5%		0.2	0.2	0.2	0.1	0.0
Capital cost	10.3%	3.1%	0.1	0.1	0.1	0.0	0.0
Operating cost	52.9%	15.6%	0.6	0.5	0.5	0.0	0.0
Revenues	36.8%	10.9%	-0.1	0.1	0.0	0.2	0.1
Transport	54.5%		0.0	0.5	0.5	0.6	0.6
Travel time	72.4%	39.5%	-0.4	0.3	0.4	0.4	0.4
Mode share	14.9%	8.2%	0.2	0.4	0.5	0.6	0.7
Transfers per trip	6.9%	3.8%	0.1	0.1	0.1	0.1	0.1
Emissions	5.7%	3.1%	0.0	0.0	0.0	0.0	0.0
Land use	15.9%		0.4	0.5	0.6	0.4	0.6
Real estate	8.6%	1.4%	0.0	0.0	0.0	0.0	0.0
Mixed-use	32.3%	5.1%	0.1	0.1	0.1	0.1	0.1
Density	26.9%	4.3%	0.3	0.4	0.4	0.3	0.3
Accessibility	32.3%	5.1%	2.4	2.4	3.1	2.4	3.1
Score			0.58	1.15	1.27	1.10	1.21
Ranking			5th	3rd	1st	4th	2nd

All of these cases change the scores. The financial-constrained and the urban-friendly cases also lead to a change in the final ranking. In the financial-constrained case, BRT2 is the chosen alternative, followed by BRT1, No Build, LRT2 and LRT1; while in the urban-friendly case, BRT2 is the chosen alternative, followed by LRT2, BRT1, LRT1 and No Build.

Table 70 - Transit user case

Criteria/Alternatives	Weights		NB	BRT1	BRT2	LRT1	LRT2
	Final	Equivalent					
Finance	15%		0.1	0.1	0.1	0.0	0,0
Capital cost	21.7%	3.3%	0.2	0.2	0.2	0.0	0,0
Operating cost	33.0%	5.0%	0.3	0.3	0.3	0.0	0,0
Revenues	45.3%	6.8%	-0.1	0.1	0.0	0.3	0,1
Transport	70%		0.2	0.8	0.8	1.0	1,1
Travel time	42.7%	29.9%	-0.2	0.2	0.2	0.2	0,2
Mode share	23.5%	16.5%	0.3	0.7	0.8	0.9	1,0
Transfers per trip	17.0%	11.9%	0.2	0.2	0.2	0.2	0,2
Emissions	16.8%	11.8%	0.0	0.0	0.0	0.1	0,1
Land use	15%		0.4	0.5	0.6	0.4	0,6
Real estate	18.1%	2.7%	0.0	0.0	0.0	0.0	0,0
Mixed-use	15.7%	2.4%	0.0	0.1	0.1	0.1	0,1
Density	31.3%	4.7%	0.3	0.4	0.4	0.3	0,3
Accessibility	34.9%	5.2%	2.6	2.6	3.3	2.6	3,3
Score			0.73	1.34	1.49	1.50	1.67
Ranking			5th	4th	3rd	2nd	1st

Table 71 - Financial-constrained case

Criteria/Alternatives	Weights		NB	BRT1	BRT2	LRT1	LRT2
	Final	Equivalent					
Finance	70%		0.4	0.5	0.4	0.1	0.0
Capital cost	21.7%	15.2%	0.2	0.2	0.2	0.0	0.0
Operating cost	33.0%	23.1%	0.3	0.3	0.3	0.0	0.0
Revenues	45.3%	31.7%	-0.1	0.1	0.0	0.3	0.1
Transport	15%		0.0	0.2	0.2	0.2	0.2
Travel time	42.7%	6.4%	-0.2	0.2	0.2	0.2	0.2
Mode share	23.5%	3.5%	0.3	0.7	0.8	0.9	1.0
Transfers per trip	17.0%	2.6%	0.2	0.2	0.2	0.2	0.2
Emissions	16.8%	2.5%	0.0	0.0	0.0	0.1	0.1
Land use	15%		0.4	0.5	0.6	0.4	0.6
Real estate	18.1%	2.7%	0.0	0.0	0.0	0.0	0.0
Mixed-use	15.7%	2.4%	0.0	0.1	0.1	0.1	0.1
Density	31.3%	4.7%	0.3	0.4	0.4	0.3	0.3
Accessibility	34.9%	5.2%	2.6	2.6	3.3	2.6	3.3
Score			0.85	1.10	1.15	0.81	0.83
Ranking			3rd	2nd	1st	5th	4th

4.6.2.9. Step 09 – Final choice and ranking

For all scenarios with and without an assigned probability (see previous sections), LRT2 was always the best alternative. The preferable alternative remains LRT2.

Table 72 - Urban-friendly case

Criteria/Alternatives	Weights		NB	BRT1	BRT2	LRT1	LRT2
	Final	Equivalent					
Finance	15%		0.1	0.1	0.1	0.0	0.0
Capital cost	21.7%	3.3%	0.2	0.2	0.2	0.0	0.0
Operating cost	33.0%	5.0%	0.3	0.3	0.3	0.0	0.0
Revenues	45.3%	6.8%	-0.1	0.1	0.0	0.3	0.1
Transport	15%		0.0	0.2	0.2	0.2	0.2
Travel time	42.7%	6.4%	-0.2	0.2	0.2	0.2	0.2
Mode share	23.5%	3.5%	0.3	0.7	0.8	0.9	1.0
Transfers per trip	17.0%	2.6%	0.2	0.2	0.2	0.2	0.2
Emissions	16.8%	2.5%	0.0	0.0	0.0	0.1	0.1
Land use	70%		2.0	2.1	2.7	2.1	2.6
Real estate	18.1%	12.7%	0.0	0.0	0.0	0.0	0.0
Mixed-use	15.7%	11.0%	0.0	0.1	0.1	0.1	0.1
Density	31.3%	21.9%	0.3	0.4	0.4	0.3	0.3
Accessibility	34.9%	24.4%	2.6	2.6	3.3	2.6	3.3
Score			2.17	2.39	2.92	2.33	2.86
Ranking			5th	3rd	1st	4th	2nd

4.7. Conclusions

The evaluation of public transport investments has changed significantly in the last decades, by incorporating environmental, social and economic concerns that were previously ignored due to the lack of adequate models, and to a low interest from decision-makers and society in general. Changes in land use, near transit stations, is a subject that is still often overlooked. These changes take longer than more traditional impacts, such as travel time savings. On the other hand, they are not quite easy to measure, requiring specific software and models for handling the associated problems.

The DSS developed in this work combines a LUT model and a MCDA model, aiming to support decision-makers on choosing public transport investment alternatives. This approach considers land use changes, that are frequently ignored mainly because they are often considered as value transfer instead of value creation, and are hard to monetize and, therefore, to be incorporated in a traditional CBA. This work is based on several assumptions justifying the adoption of a MCDA-based DSS, mainly due to the need of incorporating land use changes in decision-making. The adoption of MCDA also allowed us to incorporate a hierarchical structure relating criteria and subcriteria, value functions for each alternative, and an AHP survey for the development of priority profiles.

For the construction of value functions and the survey, the market values of American public transport projects were very useful. These values can also be used for future project benchmarking. The survey and its results are also another asset of our work, that can be adapted to other decision-making processes in the public transport sector.

In the first step of the decision-making process, the investment alternatives are defined with the help of experts and good practices. In step 02, the LUT model is applied, it has two sub-models: a traditional four-step model and an efficient land use model. This land use model incorporates, from the literature, growth indicators of property prices, population and jobs observed at station areas, i.e. within ½-mile of transit stations. With the outputs from the LUT model, a capacity check is performed before advancing to the evaluation process. Value functions are developed for each investment alternative, incorporating the outputs and the weights, obtained by a survey, answered by experts, and developed in accordance with the AHP and swing weights approach. Value functions will then produce a score for each investment alternative, allowing ranking and decision-making. Before finishing the process and making a choice, a systematic sensitivity analysis is performed.

Some issues and potential sources of uncertainty ought to be addressed. The adoption of growth indicators from the literature for the land use model does not seem very sound. As referred, there is a scarcity of empirical evidence linking increase in population and jobs, at station areas, triggered by transit investment, and therefore a broader sample of empirical findings is preferable to assign growth indicators. On the contrary, residential property price growth indicators are more abundant in the literature, as discussed in a recent paper (Higgins and Kanaroglou, 2016). For this particular case, property price indicators were chosen from findings on Boston transit system, namely the Silver line BRT and the Green line LRT, a system that is very familiar to the author and is subject of analysis in chapter 5.

Aggregating the value functions was based on several assumptions. In particular, the market values reflect recent transit and transport indicators, whereas the choice of sources consulted, and samples selected were our responsibility. In a real decision problem, this process would have inputs from experts and the decision-maker. Another source of hesitation is the survey and its results. Those doubts were addressed in the sensitivity analysis.

The case study used in this work replicates, in a straightforward way, a real situation, showing the potential of the developed DSS in effectively supporting the decision-making process. This system is, in fact, intended to support decision-making, and it should not replace the economic and financial assessment of investment alternatives, but rather complement those analyses.

5. CASE STUDY

- Introduction
- MBTA
- The Green Line extension project
- Applying the approach to GLX project
- Conclusions

5.1. Introduction

This chapter presents the case study used to test and assess the approach and the DSS developed in this work. The Green Line extension (GLX) project, currently under construction by the Massachusetts Bay Transportation Authority (MBTA), was the basis to design this case.

Located in the Northeast region of the USA, the Boston Metropolitan Area (BMA), one of the most populated US metropolitan areas, houses close to 3,2 million people distributed over 101 cities and towns (see Table 73).

Table 73 – BMA population statistics (Source: U.S. Census Bureau & CTPS, 2012).

Households	**%**		**Household Income (US$)**	**%**		**Population**	**%**
1 person	30.2		Under 10,000	7.0		Under 5 years	5.6
2 persons	31.5		10,000 to 39,999	22.7		5 to 34 years	40.8
3 persons	16.1		40,000 to 74,999	22.9		35 to 64 years	40.3
4 persons	13.5		75,000 to 149,999	30.1		65 years and over	13.4
5+ persons	8.8		150,000 and over	17.3		Employed	1,624,711
Average size	2.44		Median income	US$ 70,829		Unemployment rate	6.8%

Regarding commuting and transportation data, 71.4% and 15.4% of commuters drive or take transit to work, respectively. 84.2% of Boston households have, at least, one vehicle available, and median commute time is 26.7 minutes (see Table 74).

Table 74 – BMA commute and transport statistics (Source: U.S. Census Bureau & CTPS, 2012).

Vehicles available	**%**		**Means of commute**	**%**		**Commute time**	**%**
0	15.6		Car, truck or van	71.4		Less than 5 min.	2.3
1	36.9		Public transportation	15.4		5 to 19	32.0
2	34.7		Taxicab, Motorcycle and Bicycle	1.3		20 to 34	35.3
3	9.2		Walked	6.8		35 to 59	20.0
4+	3.3		Other means	0.62		60 min. and up	10.5
Average vehicles per household	1.49		Worked at home	4.5		Median travel time (min)	26.7

Being one of the oldest urban settlements in America, established circa 1630, BMA has the oldest US heavy and light rail systems: The Blue, Orange, Red and Green lines. The MBTA is the public agency responsible for those systems and an extensive network of commuter rail, bus, BRT and ferry services as well.

5.2. MBTA

MBTA was founded in August 1964, and currently serves about 4.8 million inhabitants in 176 cities and towns. MBTA operates 183 bus routes, 4 of which are BRTs (Silver Line), 3 subway lines (Orange, Blue and Red), 4 LRTs (Green Line), 4 trackless trolley lines, 13 commuter rail routes, THE RIDE (demand-responsive service) and ferries (MBTA, 2017a), covering 2,240 km. Figure 40 depicts the rapid transit network and main bus routes.

Figure 40 - MBTA network (Source: MBTA, 2017a).

In recent years MBTA is experiencing an overall ridership growth. In terms of daily ridership, MBTA remains the nation's 5th largest mass transit system. The average weekday ridership for the entire system is approximately 1.3 million passenger trips, i.e. vehicle boarding counts. Figure 41, Figure 42 and Figure 43 depict total annual ridership from 2011 to 2015, average weekday ridership along 2016 and MBTA’s mode share, respectively.

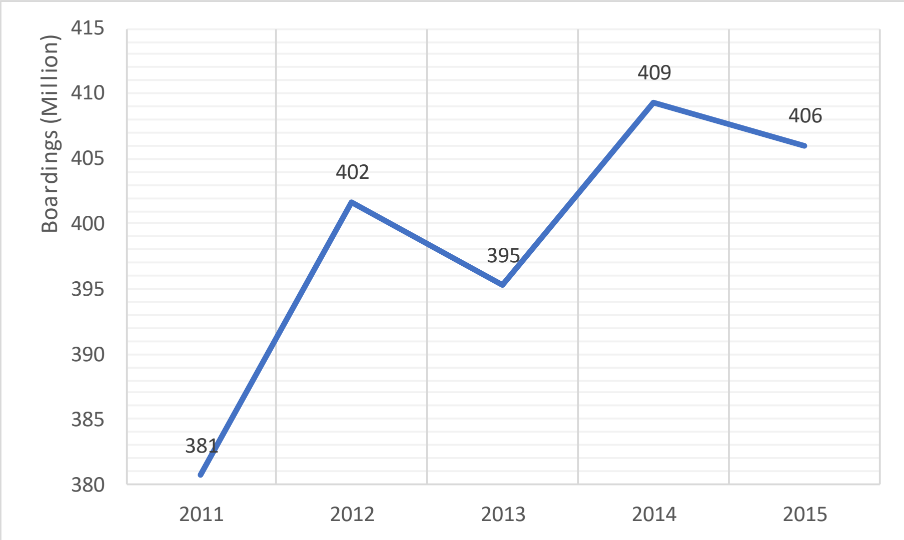


Figure 41 – MBTA yearly ridership (Source: MBTA, 2017b).

In what concerns the annual operating budget, revenues are divided in operating revenues (around 63%) and non-operating revenues (around 37%). Operating revenues include fares, advertising revenue, real estate lease payments, whereas non-operating revenues include sales taxes and contributions from the cities and towns covered by MBTA (i.e. Assessments) (MBTA, 2017b). Expenses are divided in operating expenses (about 78% of the total) and debt service (about 22%). Operating expenses cover wages, health insurance, pension benefits, fuel, payments to THE RIDE and Commuter Rail operators (MBTA, 2017b). Table 75 breakdowns budgeted operating revenues and expenses for fiscal year 2015 (from July 1st, 2014 to June 30th, 2015) (MBTA and Mass DOT, 2016).

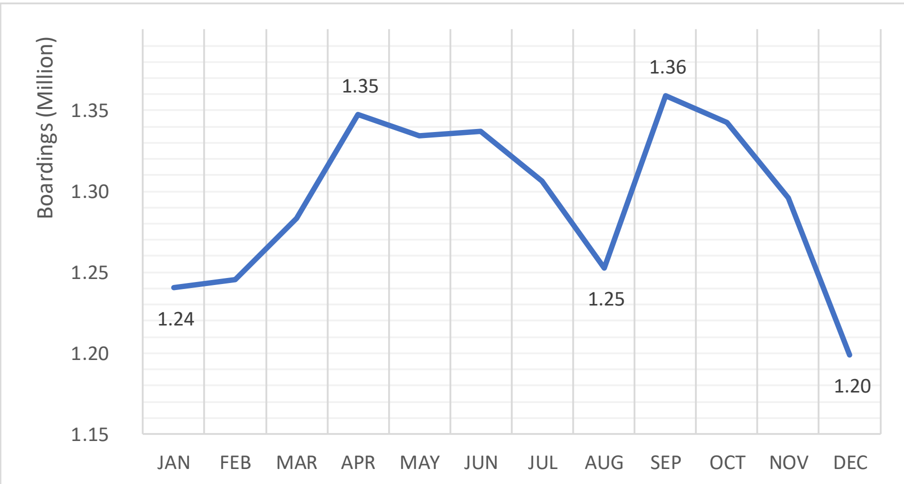


Figure 42 – MBTA daily ridership for 2016 (Source: MBTA, 2017b).

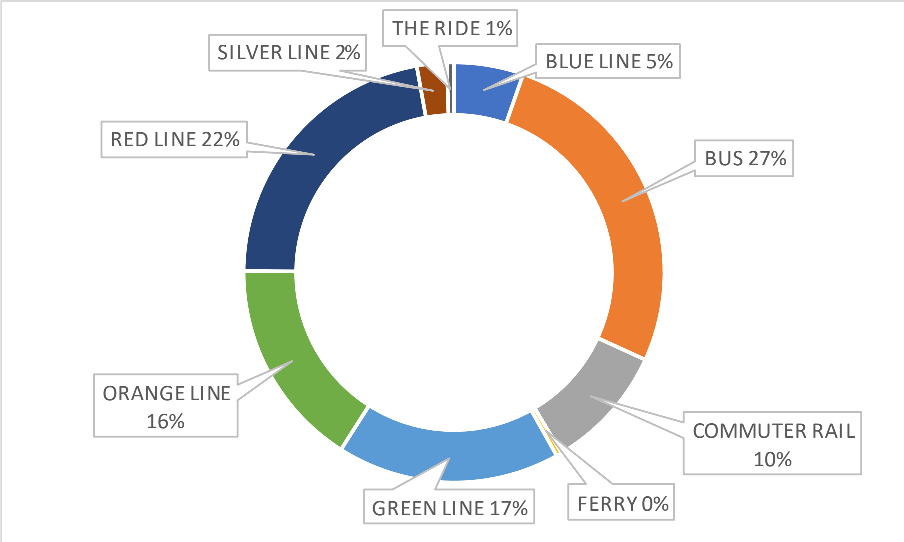


Figure 43 – MBTA mode share (Source: MBTA, 2017b).

Table 75 - MBTA operating budget for FY2015 (Source: MBTA & Mass DOT, 2016).

FY15 budgeted operating revenues			**FY15 budgeted operating expenses**		
Category	**Total (M US$)**	**%**	**Category**	**Total (M US$)**	**%**
Sales tax	811	42	Wages	493	26
Fares	598	31	Debt service	424	22
State assistance	295	15	Commuter rail and THE RIDE	506	26
Assessments	160	8	Fringes and payroll tax	249	13
Other operating revenues	49	2	Materials, supplies and services	238	12
Other income	31	2	Insurance + finance charges	23	1
Total	1943	100	Total	1933	100

Figure 44 displays revenues, expenses and structural deficit, i.e. actual expenses minus revenues, from 2011 to 2015.

In terms of farebox recovery ratio, i.e. percent of operating expenses covered by fare revenues, MBTA underperforms when compared to its peers (Mass DOT, 2014) (Figure 45). Farebox revenues currently cover about 31% of MBTA's total annual operating expenses (MBTA, 2017a) and the average fare price is US$ 1.42, while the average operating cost per trip is US$ 3.61 (MBTA and Mass DOT, 2016).

As of 2015, MBTA owes nearly US$ 9 billion in debt and interests, and has a US$ 7.3 billion maintenance backlog (Chieppo, 2015). Nonetheless MBTA, under current (from Fiscal year 2015 to 2019) Capital Investment Program, proposes investing US$ 6.2 billion (MBTA and Mass DOT, 2014) on the system, including US$ 1.4 billion for the GLX project, approved in April 2017 by the

FTA for funding and resuming construction after a new cost estimate of US$ 2.3 billion (Dungca, 2017).

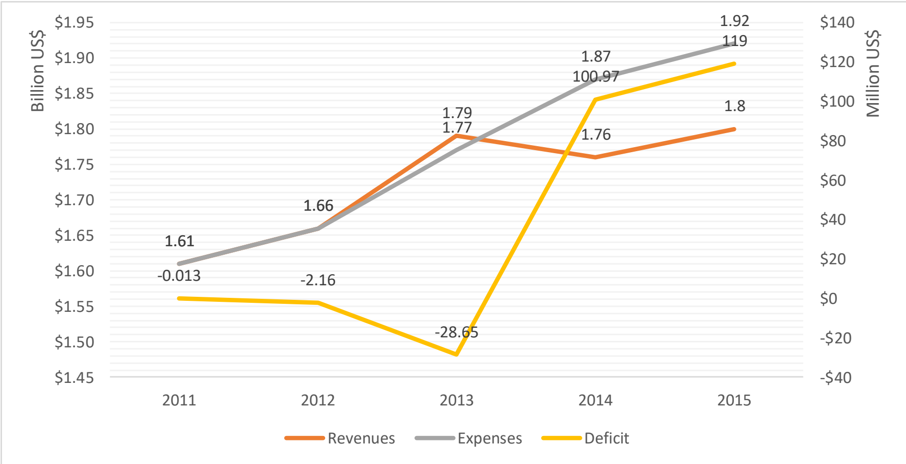


Figure 44 – MBTA yearly revenues, expenses and deficit (Source: MBTA, 2017b).

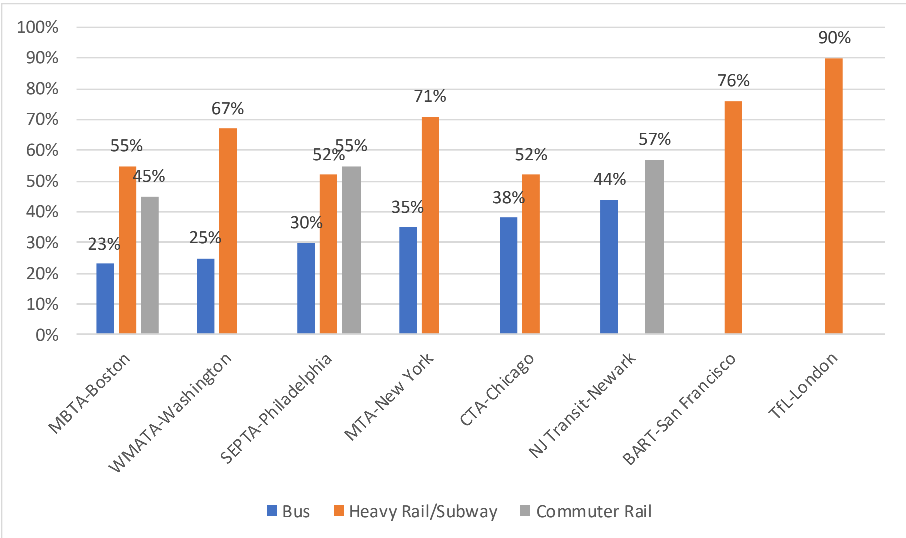


Figure 45 – Farebox recovery ratio (Source: Mass DOT, 2014).

5.3. The Green Line extension project

5.3.1. The investment alternatives

The Green Line is an LRT system connecting many destinations throughout the BMA. It has four branches that meet, and go underground through Boston's CBD, ending in the Lechmere station, in Cambridge. Figure 40 shows the current Green Line network in green. The GLX project will further extend BMA's transit system beyond Lechmere, serving Somerville and Medford. The city of Somerville comprises the most part where the GLX project sits, and is one of the densest cities of America and the densest city of Massachusetts, with 7,117 inhabitants per square kilometer (Mass DOT, 2016).

The first list of GLX alternatives proposed on the *Draft Environmental Impact Report / Environmental Assessment (DEIR/EA)* back in 2009, included the “No Build” option and eight “Build” alternatives. The “No Build” alternative would not improve corridor mobility, transit ridership, regional air quality, ensure equitable distribution of transit services, or support opportunities for TOD (FTA and EOT, 2009), and it was therefore early dismissed. Table 76 depicts the “Build” alternatives.

Table 76 - GLX "Build" alternatives (Source: FTA & EOT, 2009).

Alternatives	**Mode**	**Capital cost (2008 M US$)**	**Operating cost (2008 M US$/year)**	**2030 new boardings/day**
BA (based on MBTA 80 and 87 bus routes)	BRT	146.2	13.7	2,800
A1 – Medford Hillside and Union Square (via commuter rail right-of-way)	LRT	804.8	21.3	7,900
A2A – Mystic Valley Parkway / Route 16 (with parking) and Union Square (via commuter rail right-of-way)	LRT	959.3	23.7	8,900
A2B – Mystic Valley Parkway / Route 16 (without parking) and Union Square (via commuter rail right-of-way)	LRT	951.8	23.7	8,600
A3 – Medford Hillside and Union Square (via Somerville Avenue)	LRT	829.8	22.1	7,700
A4 – Mystic Valley Parkway / Route 16 (with parking) and Union Square (via Somerville Avenue)	LRT	984.3	24.5	8,700
A5 – Mystic Valley Parkway / Route 16 (with parking)	LRT	870	28.2	10,500
A6 –Union Square (via commuter rail right-of-way)	LRT	370.6	8.1	3,900

Alternative 1 (A1) was selected, as it provides a balance of cost, ridership, and environmental impacts (FTA and EOT, 2009) (Figure 46). It will operate in existing commuter rail rights-of-way, reducing the need to purchase local property and minimizing construction impacts. *Green Line D* will end at College Avenue, with headways equal to those of the existing *Green Line D* branch service: five minutes in the morning and evening peak periods, and 10 minutes during off-peak

periods. *Green Line E* will end at Union Square, in downtown Somerville, with headways equal to those of the existing *Green Line E* branch service: six minutes in the morning peak period, five minutes in the evening peak period, and between nine and 10 minutes during, off-peak periods. Both branches would operate between 5 AM and 1 AM. Project completion is due at December 2021.

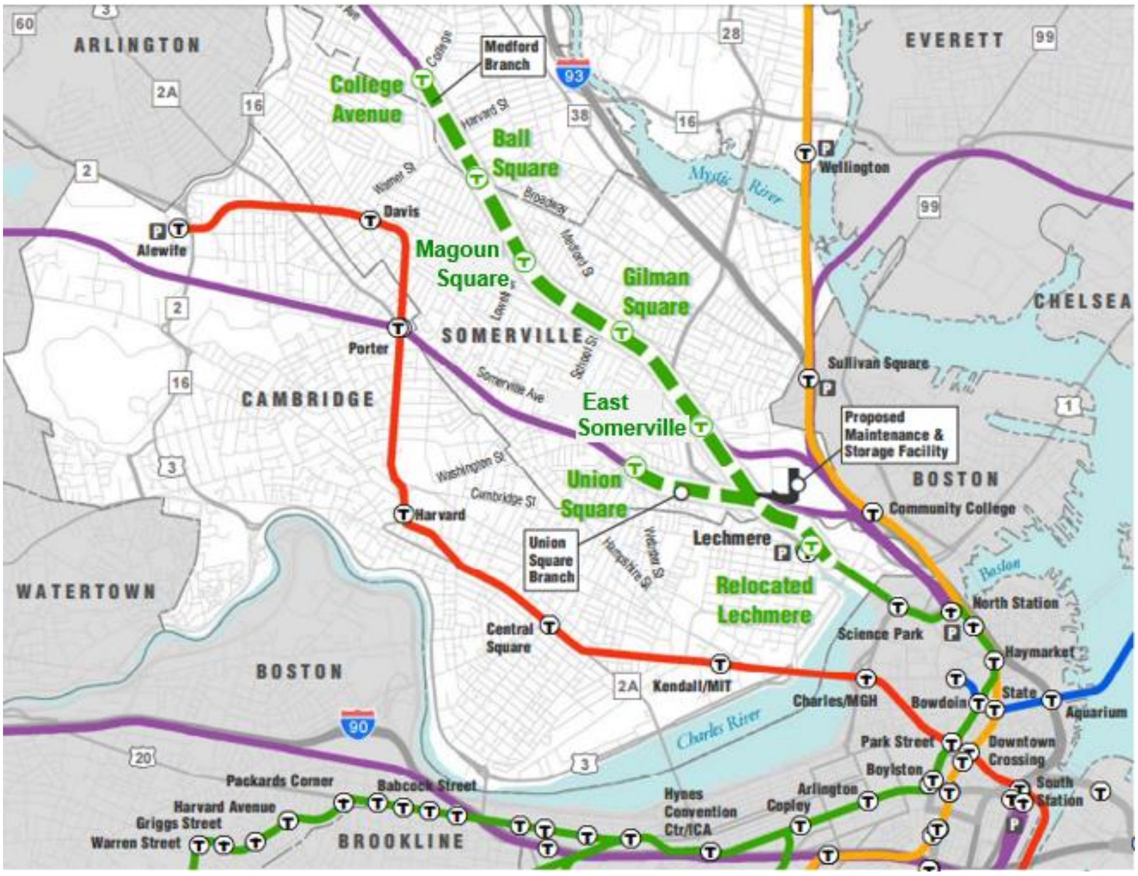


Figure 46 - Proposed GLX alignment (Source: Mass DOT, 2016).

The GLX project is required by the *Massachusetts Department of Environmental Protection's State Implementation Plan* to comply with *Federal Clean Air Act* standards. The project also fulfills a longstanding commitment to improve air quality and increase public transportation in the BMA, as a mitigation measure for the Boston Central Artery / Highway Tunnel, i.e. the Big Dig, a project that was completed in 2007 (FTA, 2016e).

We now analyze the chosen alternative (A1) according to the aspects (subcriteria) presented in chapter 4: capital costs, operating costs, revenues, travel time, mode share, transfers, emissions, real estate, density, mixed-use and accessibility. We also discuss the BRT alternative (baseline alternative - BA) that was early dismissed by the decision-makers. This exercise aims at showing the potential of our DSS in enhancing the decision-making process.

5.3.2. Capital costs, operating costs and revenues

After a period of some uncertainty about the project's future, mainly due to capital cost misestimations, FTA and the *Commonwealth of Massachusetts* secured, each, approximately US$ 996 million for funding the GLX project, allowing the project to continue, as of April, 2017 (Dungca, 2017). Moreover, US$ 50 million are secured by the City of Somerville, US$ 25 million by the City of Cambridge, and US$ 157 million is secured by Boston Region Metropolitan Planning Organization (MPO). This yields a funding gap of approximately US$ 64 million, that is secured by additional contributions from the Massachusetts Department of Transportation and the Commonwealth (Mass DOT, 2017). This capital costs estimation of US$ 2.3 billion includes the acquisition of 24 LRT vehicles (Figure 47), budgeted in US$ 183 million (Mass DOT, 2017). Considering its 6.9 km of the line length, the estimated capital cost is US$ 333 million/km.

Figure 47 - GLX vehicles (Source: Railway Gazette, 2014).

Operating costs are estimated at US$ 26 million/year. That costs are partially offset by fare revenues of US$ 3 million/year, leading to a US$ 23 million/year net operating deficit (Mass DOT, 2017). Considering the 6.9 km of line length, the estimated operating cost is US$ 3.8 million/year/km.

The estimated (2030) daily ridership (boardings and alightings) for the seven stations is 48,560 trips (Mass DOT and MBTA, 2011). Considering the 6.9 km of line length, estimated revenue is 7,038 trips/day/km. Table 77 presents the figures for the different stations.

Table 77 - GLX estimated daily ridership

Stations	Boardings	Alightings
Lechmere	8.820	8,820
East Somerville	2.830	2,830
Gilman Square	3.930	3,930
Magoun Square	1.140	1,140
Ball Square	1.850	1,850
College Avenue	2.140	2,140
Union Square	3.570	3,570
Total	24.280	24,280
Final total	48.560	

5.3.3. Travel time, mode share, transfers and emissions

The estimated (2030) travel time between College Avenue station and Lechmere Station is 9.5 minutes, with headways equal to those of the existing *Green Line D* branch service. The estimated travel time between Union Square and Lechmere station is 4.5 minutes, with headways equal to those of the existing *Green Line E* branch service (MBTA and Mass DOT, 2010). These figures do not account for access time and waiting times.

The current (2015) Somerville commute mode share (U. S. Census Bureau, 2014) is depicted in Figure 48.

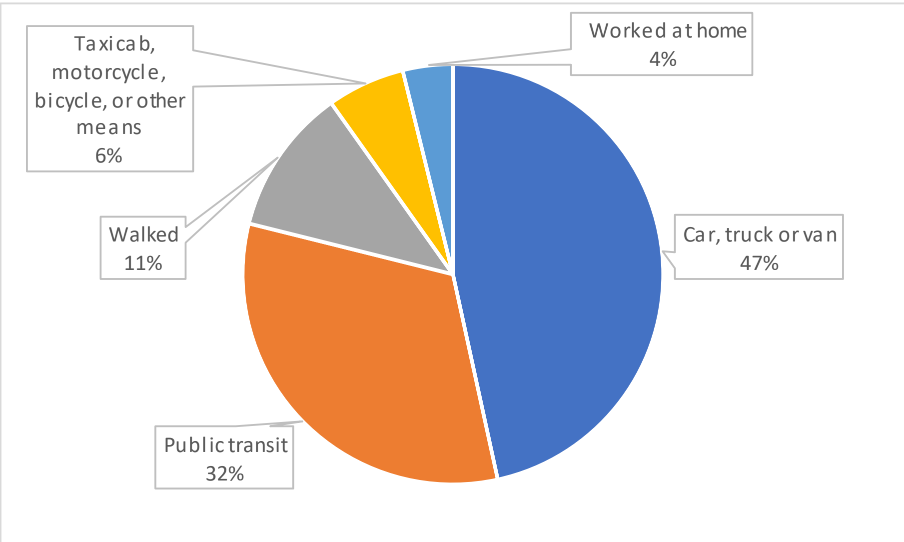


Figure 48 - Current Somerville mode share (Source: U. S. Census Bureau, 2014).

Despite having only one T station (the Red Line's Davis Station) and 6 MBTA bus routes, Somerville, the city where most of the GLX project sits, has already a high non-private motorized mode share.

Notwithstanding, transit ridership forecasts on the GLX indicate mode shares approaching those currently observed near Davis station, i.e. between 40% and 60% (CTPS, 2009).

One of the main benefits of the GLX project is the elimination of bus transfers at Lechmere station. Currently, most MBTA bus routes serving Somerville depart from Lechmere, thus transit users bound to Boston must transfer there to the Green Line LRT service.

Finally, in 2030, the GLX project should reduce CO_2 emissions by 17,682 kg/day when compared to the No Build alternative for the same year (Mass DOT and MBTA, 2011).

5.3.4. Real estate, density, mixed-use and accessibility

As of January 2016 (Figure 49), Somerville's median home price was US$ 437 per square feet or US$ 4,704 per square meter (Zillow, 2016). Projections on the potential increase in home prices at GLX station areas are not available.

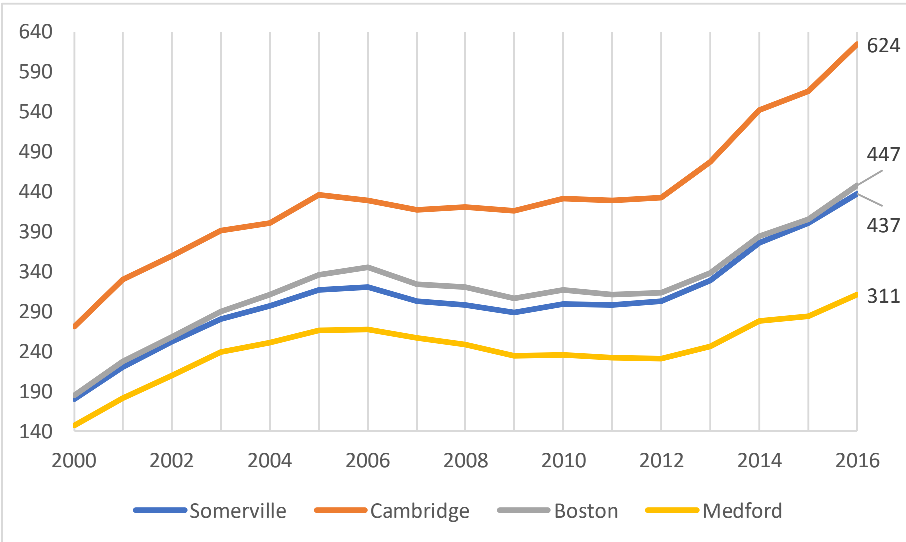


Figure 49 - Median home price per square feet (Source: Zillow, 2016).

Somerville will benefit from the GLX project, mainly at station areas. The mayor, Joseph A. Curtatone, is pro-GLX and pro-TOD (Salvucci, 2015). He changed zoning ordinances to favor TOD, and worked with land and shop owners near future transit stations, to have their commitment about the project. The city has also acquired some land and made good deals with previous property owners. That was the case, for example, of a scrapyard owner near the future Union square station, which was relocated so that the land could be reused to build high density (Salvucci, 2015). Union Square has a US$ 1 billion redevelopment plan expected to dramatically change downtown Somerville (Sayer, 2017). As of January 2014, nine large-scale projects were completed or were under construction in station areas and seven large development projects were planned or proposed (FTA, 2016e).

Estimated (2030) *changes in population and employment* at station areas (1/2-mile radius) are depicted on Table 78 (MBTA and Mass DOT, 2011).

Table 78 - Estimated population, jobs and entropy at GLX station areas

Stations	Pop. density (Pers./sq. km)			Job density (Jobs/sq. km)			Entropy		
	2010	2030	growth	2010	2030	growth	2010	2030	growth
Lechmere	5,205	7,292	40.1%	8,664	10,533	21.6%	95%	98%	2.2%
East Somerville	6,193	7,177	15.9%	3,532	4,313	22.1%	95%	95%	1.0%
Gilman Square	9,710	9,660	-0.5%	1,692	1,867	10.3%	61%	64%	5.5%
Magoun Square	9,050	9,339	3.2%	1,438	1,543	7.2%	58%	59%	2.1%
Ball Square	7,172	7,349	2.5%	1,327	1,411	6.4%	62%	64%	1.9%
College Avenue	6,205	6,280	1.2%	1,530	1,633	6.7%	72%	73%	2.4%
Union Square	9,717	10,546	8.5%	3,831	3,999	4.4%	86%	85%	-1.2%
All station areas	7,516	8,185	8.9%	3,343	3,861	15.5%	89%	90%	1.6%

Regarding accessibility, analyses and estimations (2030) were performed for jobs reachable by transit within 40 minutes (Mass DOT and MBTA, 2011) for environmental justice (EJ) areas, i.e. identifiable geographic areas of minority and low-income populations and non-environmental justice (Non-EJ) areas.

Table 79 - Estimated accessibility

Alternative	EJ	Non-EJ	Total jobs in the BMA	% EJ	% Non-EJ
No Build	482,390	410,529	3,402,940	14%	12%
GLX	501,040	430,083		15%	13%

5.3.5. Some considerations on the baseline alternative

The baseline alternative (BA) is a low-cost transit service aiming at providing a service level equivalent to that of A1. BA is an enhanced, limited stop BRT-like service (Figure 50).

Although ending at College Avenue station, the BA would serve one more station than the A1 alternative (see Figure 50). For the Medford Branch (from Lechmere to Mystic Valley Parkway / Route 16), the BA would have an enhanced version of the existing MBTA Route 80 bus service with stop spacings and headways similar to A1. For the Union Square Branch (from Lechmere to Union Square), a shuttle service would be implemented, based on the existing MBTA Route 87 bus service, with stop spacings and headways similar to A1. The estimated length (until College Avenue and Union Square) is 7.8 km. The BA was expected to generate new systemwide transit ridership of 2,800 linked trips per day (2030) (Table 76).

Figure 50 - BA and A1 alternatives from GLX project (Source: FTA & EOT, 2009).

The enhanced Route 80 (College Avenue – Lechmere) is estimated to have a travel time of approximately 23 minutes during the peak periods, an improvement of about three minutes, when compared to the current bus service. The enhanced Route 87 (Union Square – Lechmere) is estimated to have a travel time of approximately 15.5 minutes during the peak periods, an improvement of about two minutes, when compared to the current bus service (FTA & EOT, 2009).

The capital cost (2011) of the BA would be approximately US$ 168 million. Its operating costs (2011) are estimated to be approximately US$ 15.2 million/year (FTA & EOT, 2009).

Some of the reasons for dismissing the BA and choosing A1 are related to BA's weakness in sufficiently improving mobility in the corridor (as it would still require transfers at Lechmere), to the fact that it does not meet the Commonwealth's overall goal for air quality benefits, and because it does not sufficiently promote opportunities for TOD and economic development in the corridor (FTA & EOT, 2009).

Table 80 compares the two alternatives, with the information presented throughout this chapter. These figures were computed based on multiple years, reflecting forecasted costs or benefits for the different investment alternatives. Capital and operating costs are from 2008, one of the first cost estimations. Since then, A1 capital and operating cost estimations increased, reaching US$ 333million/km and US$ 3.8million/year/km, respectively. Such trend could also take place in the case of the BA.

Table 80 - Comparisons between BRT and LRT alternatives for the GLX project

Subcriterion	BA	A1
Capital costs (2008 M US$/km)	19	103
Operating costs (2008 M US$/year/km)	1.8	2.7
Revenues (2030 new boardings/day/km)	359	1.013
Medford Branch travel time (2030 minutes)	23	9,5
Union Sq. Branch travel time (2030 minutes)	15.5	4.5
Transfers	1	0
Density (2030 pop/km^2)	---	8,185
Mixed-use (2030 entropy)	---	90%
Accessibility (2030 %)	---	14%

Moreover, A1 outperforms BA on the estimated (2030) revenues and travel times. Transfer figures do not reflect the estimated (2030) number of transfers per trip but are rather a result of a key issue considered for choosing A1: while BRT-LRT transfers would continue in Lechmere under the BA, A1 would allow a direct trip from Somerville to Boston, sidestepping the need of transferring in Lechmere. The estimated values (2030) for density, mixed-use and accessibility are only available for A1. However, considering the estimated travel times for BA, the accessibility for BA would be lower than that for the A1.

5.4. Applying the approach to the GLX project

The BMA is one of the most populated US metropolitan areas with an extensive and integrated transit system managed by MBTA. MBTA's rail network, also known as "T", is expanding beyond Lechmere, the current terminus for the Green Line service in Cambridge. This expansion, also known as the "GLX" project, will mainly serve Somerville, the densest city in Massachusetts.

The decision-making process and construction period associated to the GLX project were lengthy and uncertain, largely due to capital costs misestimations, starting back in 2005, with the *"Beyond Lechmere" Northwest Corridor* report (VHB, 2005), and with service estimated to commence in 2022. In the beginning, a set of investment alternatives were proposed, including a BRT system, and an extension of the current LRT network. We will revisit the BRT and LRT alternatives, along with the No Build case, and test these alternatives with the decision support system designed in this work.

As described, the first discussions about the GLX project considered a set of investment alternatives, which included, amongst others, the A1 LRT alternative, a BRT alternative (BA), and the No Build (NB) option. BA and NB were early dismissed, allowing decision-makers to sponsor A1 and seek for FTA funding under the New Stars Capital Investment Program (Mass DOT and MBTA, 2011).

In this section, we will first present the investment alternatives proposed: NB, BA[21] (Bus Rapid Transit) and A1[22] (Light Rail Transit). We will then describe the *MIT Boston Metro Region Four Step Model* (MIT-FSM) that was used to provide inputs to the DSS (this model is regularly used by the Department of Urban Studies and Planning at MIT).

After checking the capacity threshold, several analyses on the decision criteria will be presented. Many subcriteria were estimated by the MIT-FSM, but some were estimated using external sources and methods that will be described in detail. The following steps of the decision-making process will then be presented, namely: the value functions; the expert's priority profiles; choice and ranking; the sensitivity analysis; and the final choice. The final ranking has NB in the first place, BRT in the second place, and LRT in the third place.

5.4.1. Definition of investment alternatives

As referred, there are three investment alternatives for this case study: No Build (NB), Bus Rapid Transit (BRT), and Light Rail Transit (LRT). On all three alternatives, all other components of transit, pedestrian and road network remain the same. These alternatives resemble, as much as possible, the ones proposed on the GLX project, but the results of the study may obviously be different due to the adoption of different models and assumptions.

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[21] Henceforth called BRT.

[22] Henceforth called LRT.

LRT

The LRT (A1 alternative in the GLX project) was expected to begin operation in 2022. It will extend the MBTA's light rail Green Line, nowadays ending in Lechmere, along two new branches: College Avenue and Union Square, with 7 new stations, including relocating the existing Lechmere station. It will use commuter rail tracks and ROW, differing from most Green Line ROW, which typically allows traffic crossings, must stop at traffic lights and, in some streets, runs in mixed-traffic (Figure 51). Hence, the LRT alternative will have ROW A (see section 2.2.1) – see Figure 52.

Figure 51 - A typical at ground level Green Line station (Source: Phelan, 2011).

This alternative will run light rail trains similar to those used nowadays on the rest of the green Line, with headways equal to those of the existing *Green Line D* to the College Avenue branch service: five minutes in the morning and evening peak periods, and 10 minutes during off-peak periods, and *Green Line E* to Union Square, in downtown Somerville: six minutes in the morning peak period, five minutes in the evening peak period, and between nine and ten minutes during off-peak periods.

Both branches would operate between 5 AM and 1 AM. The dwell time is 20 seconds in stations with pre-payment systems, and up to one minute in regular stations without a pre-payment system. The average speed along the College Avenue branch (the longest branch) is 23.9 km/h and along the Union Square branch (the shortest) is 21.0 km/h. The total length for the two branches is 6.9 km (the shortest branch is 1.6 km and the longest is 5.3 km), and the average station spacing is 1.2 km.

Regarding vehicle capacity, an LRT composition has 2 vehicles that can carry, each one, up to 104 passengers, with a total of 208 passengers per transit trip.

Figure 52 - The LRT alternative

<u>*No Build*</u>

The NB alternative (see Figure 54) keeps the transit network exactly as it is today. The two main bus routes serving the study area today are MBTA 80 and 87 outbound from Lechmere (the 80 roughly serves along the College Avenue branch, and the 87, the Union Square branch). They operate standard 40 feet MBTA buses with approximately 20 minutes' frequency during AM peak hours. The bus capacity is 95 passengers.

The two lines are longer than the GLX project, ending farther away from College Avenue or Union Square. Yet, for this case study, only the sections serving the branches were analyzed. They also have much more stops than the other alternatives, amounting to 17 stops along Route 80, and 11 stops along Route 87. They run in mixed traffic lanes without any preference measures such as off-board fare collection, bus lanes, or busways. Hence, this alternative is ROW C (see section

2.2.1). The Mean speed along the College Avenue Branch (Route 80) is 16.6 km/h, and along the Union Square Branch (Route 87) is 16.5 km/h.

BRT

The BRT investment alternative is based upon MBTA bus routes 80 and 87, running roughly along the same path. However, it will operate more like the Silver Line BRT service in south Boston (services in silver on Figure 40), with the same number of stops and frequencies as the LRT alternative. The BRT length is 5.9 km on the College Avenue branch, and 1.9 km on the Union Square branch, in a total of 7.8 km. The currently existing Silver Line system is a BRT system with ROW B, i.e. buses run mainly on curbside bus lanes and, in some cases, on dedicated busways, without pre-payment systems or preference at intersections (Figure 53). Dwell times for both the BRT and the NB are 24 seconds. The BRT will operate only articulated buses with capacity of 138 passengers. The mean speed along the College Avenue Branch (Route 80 BRT) is 20.6 km/h, and along the Union Square Branch (Route 87 BRT) is 29.5 km/h.

Figure 53 - Silver Line BRT bus (Source: Lawrence, 2015) (left) and typical Silver Line BRT stop (Source: Nickerson, 2010) (right).

For all alternatives, it is assumed the service starts in 2020. Nevertheless, the analysis of the outputs was done for 2030, the so-called horizon year.

5.4.2. Land use and transport model

To complete step 2 of the process, the *MIT Boston Metro Region Four Step Model* (MIT-FSM) was employed, helping calculate the value of some decision criteria: revenues, average travel time, non-private motorized mode share, and average transfers per trip. The remaining criteria were estimated using different methods which, in some cases, use part of the MIT-FSM results and findings as described in some reviewed literature. The MIT-FSM approach is described below, and the other used methods, are presented later in this work.

Figure 54 – NB and BRT alternatives

<u>*MIT Boston Metro Region Four Step Model*</u>

The MIT-FSM approach was developed by Mikel Murga from MIT and is mainly used at MIT's Department of Urban Studies and Planning. Here we briefly describe the model, using largely two master theses authored by Michael Dowd (Dowd, 2015) and Yafei Han (Han, 2015). Based on the *Cube Voyager* modeling software platform, MIT-FSM consists of 986 zones covering 164 towns of eastern Massachusetts, with about 4.5 million inhabitants and 1.7 million households in 2010.

<u>*The inputs*</u>

Demographic and employment data for 2010 comes mainly from the Central Transportation Planning Staff (CTPS) but also from the U.S. census and the 2010-2011 Massachusetts Travel Survey (Dowd, 2015; Han, 2015). Road, rail, transit and pedestrian networks are also in the model, with three major travel modes: automobile, transit and walking. Households are divided in 224 types, per size, number of workers and vehicles, with the number of vehicles predicted with an exogenous vehicle ownership model (Han, 2015). Those households are further rearranged in four income levels, for trip generation estimation. For mode split they are furthermore segmented in *choice* and *captive*: captive is a household with more workers than vehicles, whilst the other are choice. MIT-FSM does not contain cycling, taxis, freight and visitors / tourists.

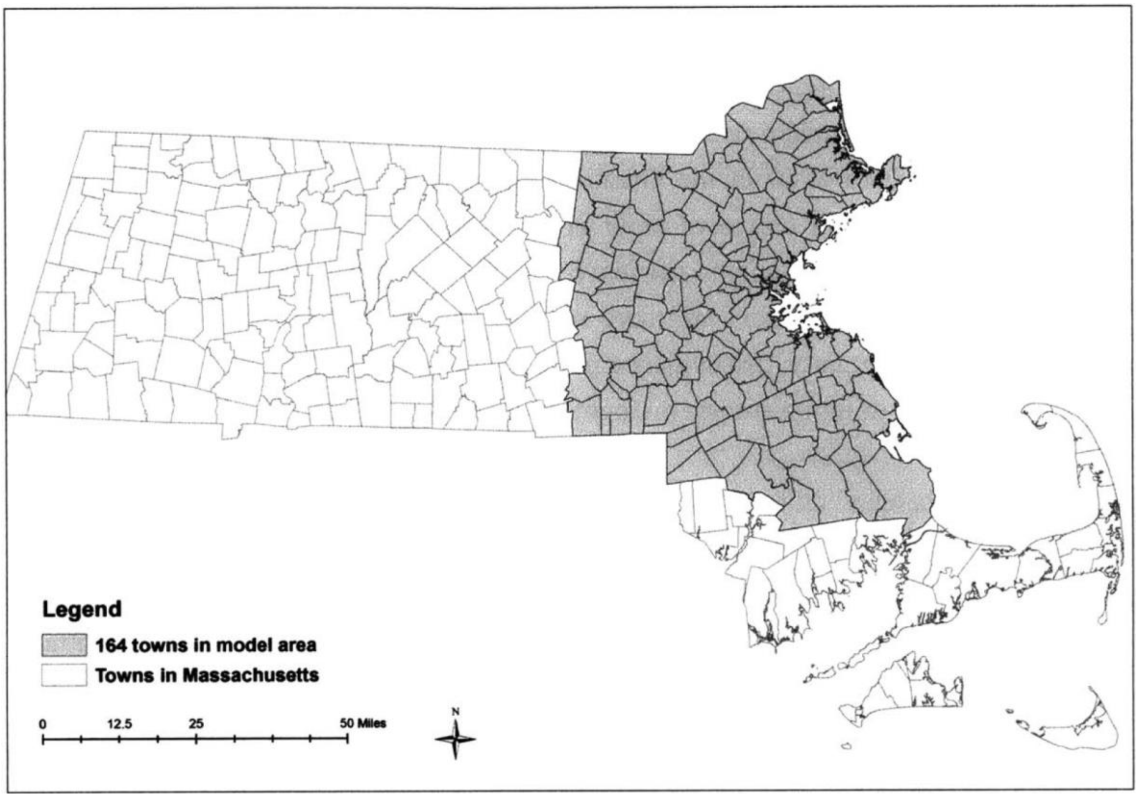

Figure 55 - Model area (Source: Han, 2015).

<u>The model</u>

MIT-FSM is a four-step model (trip generation, trip distribution, mode split, and assignment). Trip generation will partition trips by: income levels; by purpose (i.e. home-based work, home based shopping, home based others, non-home-based work and non-home based other); and by period of day (peak (AM or PM), midday and rest of the day). All home-based work trips are considered to be in peak periods, while the remaining trips happen in midday and in the rest of the day. This step relies on an exogenous trip generation model (Han, 2015).

Trip distribution is based on a gravity model, that distributes the trips according to their relative attractiveness and to a friction factor, i.e. a travel time impedance function. This step has more than one interaction, because in the first interaction travel times are on free-flow uncongested conditions. After running the assignment step, travel times are updated until reaching acceptable values.

Mode split takes the Origin-Destination matrices produced in the trip distribution step and splits the trips into five transportation modes, trip purpose, and choice or captive status through a multinomial logit approach. *Captive* have three modes (walk access transit (WAT), walk (WALK) and auto passenger (APAX)) and *choice* have four modes (walk access transit (WAT), single occupancy vehicle (SOV), walk (WALK) and drive access transit (DAT)).

The assignment step has two parts: auto assignment (done by a Stochastic User Equilibrium) and transit assignment (with a Probabilistic Multimodal model).

The MIT-FSM outputs

MIT-FSM delivers multiple outputs such as travel time, O/D matrices, traffic flows and transit ridership. For this research, the outputs (for 2030) are the following (see the Appendix for a detailed description).

1. AM home-based work O/D matrices by mode;
2. AM transit travel time skims[23];
3. 24-hour total number of transfers;
4. AM and 24-hour transit ridership.

The model was run for all three investment alternatives, for the year of 2030. Population and household growth rates were drawn from MAPC (2014) while employment growth rates were drawn from MPO (2015).

5.4.3. Capacity threshold check

As referred, one of the model outputs is the data on AM transit ridership. The AM period is 3 hours long, and therefore, to verify the capacity threshold, the peak hour within the AM period must be extracted. To do this, we considered that 50% of all transit passengers traveling during the AM period do it in the peak hour, while the others travel in the other two hours. The following tables present ridership estimations for the AM peak hour for Bus 80 and 87, BRT 80 and 87 and LRT on Union Square and College Avenue branches, on both directions. The following tables only present data regarding the transit service cruising the study area, and do not cover all transit stops (only those with passengers either boarding or alighting).

[23] Skims are any type of Origin/Destination matrix that may contain travel times, distances, costs, etc.

Table 81 – Bus Route 80 (NB investment alternative)

80 (Lechmere – College Avenue)						80 (College Avenue – Lechmere)					
Stop №	On	Off	Vol (1hr)	Line capacity (1hr)	Load factor (%)	Stop №	On	Off	Vol (1hr)	Line capacity (1hr)	Load factor (%)
1	9	0	9	285	3%	1	3	6	13	285	5%
2	19	2	26	285	9%	2	0	2	11	285	4%
3	14	2	38	285	13%	3	5	2	14	285	5%
4	10	1	47	285	16%	4	8	5	16	285	6%
5	4	0	50	285	18%	5	39	6	49	285	17%
6	9	44	15	285	5%	6	3	9	44	285	15%
7	4	5	13	285	5%	7	3	22	25	285	9%
8	31	7	37	285	13%	8	1	3	22	285	8%
9	16	6	46	285	16%	9	-	4	19	285	7%
10	2	36	11	285	4%	10	2	10	10	285	4%
11	1	10	2	285	1%	11	1	2	10	285	4%
						12	0	9	0	285	0%
Total	119	113	-	-	-	Total	65	80	-	-	-

Table 82 – Bus Route 87 (NB investment alternative)

87 (Lechmere – Union Square)						87 (Union Square – Lechmere)					
Stop №	On	Off	Vol (1hr)	Line capacity (1hr)	Load factor (%)	Stop №	On	Off	Vol (1hr)	Line capacity (1hr)	Load factor (%)
1	11	0	11	285	4%	1	2	2	13	285	5%
2	20	2	28	285	10%	2	3	1	15	285	5%
3	13	3	39	285	14%	3	1	0	15	285	5%
4	10	1	48	285	17%	4	1	5	11	285	4%
5	4	0	52	285	18%	5	2	3	10	285	4%
6	22	49	25	285	9%	6	1	0	11	285	4%
7	0	6	19	285	7%	7	0	11	0	285	0%
8	0	4	15	285	5%						
9	0	2	13	285	5%						
10	0	4	9	285	3%						
11	0	3	6	285	2%						
Total	80	74	-	-	-	Total	10	22	-	-	-

The tables for the BRT investment alternative are presented below, with data regarding bus route 80 and 87 (which will remain operating despite the new BRT system) and BRT College Avenue branch and BRT Union Square branch.

Table 83 – Bus Route 80 (BRT investment alternative)

80 (Lechmere – College Avenue)						**80 (College Avenue – Lechmere)**					
Stop №	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**	**Stop №**	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**
1	14	0	14	285	5%	1	1	7	10	285	4%
2	17	5	26	285	9%	2	0	2	7	285	2%
3	11	5	33	285	12%	3	2	2	7	285	2%
4	8	1	40	285	14%	4	2	3	6	285	2%
5	1	0	40	285	14%	5	7	3	11	285	4%
6	0	33	7	285	2%	6	2	0	12	285	4%
7	2	7	3	285	1%	7	11	6	17	285	6%
8	9	1	11	285	4%	8	1	0	17	285	6%
9	1	9	3	285	1%	9	0	6	12	285	4%
10	1	2	2	285	1%	10	2	8	6	285	2%
						11	1	3	4	285	1%
						12	0	4	0	285	0%
Total	64	63	-	-	-	Total	29	44	-	-	-

Table 84 – Bus Route 87 (BRT investment alternative)

87 (Lechmere – Union Square)						**87 (Union Square – Lechmere)**					
Stop №	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**	**Stop №**	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**
1	15	0	15	285	5%	1	9	6	17	285	6%
2	18	5	27	285	9%	2	1	2	15	285	5%
3	11	5	33	285	12%	3	2	7	11	285	4%
4	8	1	40	285	14%	4	1	3	9	285	3%
5	1	0	40	285	14%	5	0	9	0	285	0%
6	2	37	5	285	2%						
7	1	0	6	285	2%						
8	1	3	4	285	1%						
Total	57	31	-	-	-	Total	13	27	-	-	-

Table 85 – College Avenue branch (BRT investment alternative)

BRT (Lechmere – College Avenue)						**BRT (College Avenue – Lechmere)**					
Stop №	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**	**Stop №**	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**
1	52	0	52	1,656	3%	1	26	0	26	1,656	2%
2	22	12	62	1,656	4%	2	32	5	53	1,656	3%
3	75	40	97	1,656	6%	3	23	13	63	1,656	4%
4	24	22	99	1,656	6%	4	63	17	109	1,656	7%
5	9	47	61	1,656	4%	5	29	66	72	1,656	4%
6	0	61	0	1,656	0%	6	0	72	0	1,656	0%
Total	182	182	-	-	-	Total	173	173	-	-	-

Table 86 – Union Square branch (BRT investment alternative)

BRT (Lechmere – Union Square)						BRT (Union Square – Lechmere)					
Stop №	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**	**Stop №**	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**
1	39	0	39	1,380	3%	1	34	0	34	1,380	2%
2	0	39	0	1,380	0%	2	0	34	0	1,380	0%
Total	39	39	-	-	-	Total	34	34	-	-	-

The tables for the LRT investment alternative are presented below, with data regarding bus routes 80 and 87 (which will remain operating despite the new LRT system), and LRT College Avenue branch (Line D) and LRT Union Square branch (Line E).

All transit services respect the 90% load factor and, therefore, the investment alternatives do not need to be redesigned.

Table 87 – Bus Route 80 (LRT investment alternative)

80 (Lechmere – College Avenue)						80 (College Avenue – Lechmere)					
Stop №	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**	**Stop №**	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**
1	8	0	8	285	3%	1	0	12	11	285	4%
2	1	3	6	285	2%	2	0	5	7	285	2%
3	2	3	5	285	2%	3	1	1	6	285	2%
4	1	1	5	285	2%	4	0	4	3	285	1%
5	0	5	0	285	0%	5	0	1	2	285	1%
6	1	0	1	285	0%	6	1	1	2	285	1%
7	5	0	6	285	2%	7	0	1	0	285	0%
8	0	5	2	285	1%	8	1	0	1	285	0%
9	1	1	2	285	1%	9	0	2	0	285	0
Total	19	18	-	-	-	Total	3	26	-	-	-

Table 88 – Bus Route 87 (LRT investment alternative)

87 (Lechmere – Union Square)						87 (Union Square – Lechmere)					
Stop №	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**	**Stop №**	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**
1	9	0	9	285	3%	1	0	1	4	285	1%
2	2	3	7	285	2%	2	1	1	4	285	1%
3	2	3	6	285	2%	3	0	4	0	285	0
4	1	1	6	285	2%						
5	2	6	3	285	1%						
Total	16	13	-	-	-	Total	1	6	-	-	-

Table 89 – College Avenue branch (LRT investment alternative)

LRT (Lechmere – College Avenue)						LRT (College Avenue – Lechmere)					
Stop №	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**	**Stop №**	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**
1	9	315	403	2,496	16%	1	149	0	149	2,496	6%
2	27	166	264	2,496	11%	2	156	5	300	2,496	12%
3	26	150	140	2,496	6%	3	129	9	420	2,496	17%
4	18	63	95	2,496	4%	4	430	17	833	2,496	33%
5	3	33	65	2,496	3%	5	243	54	1022	2,496	41%
6	0	65	0	2,496	0%	6	232	65	1189	2,496	48%
Total	83	792	-	-	-	Total	1,339	150	-	-	-

Table 90 – Union Square branch (LRT investment alternative)

LRT (Lechmere – Union Square)						LRT (Union Square – Lechmere)					
Stop №	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**	**Stop №**	**On**	**Off**	**Vol (1hr)**	**Line capacity (1hr)**	**Load factor (%)**
1	10	82	108	2,080	5%	1	95	0	95	2,080	5%
2	0	108	0	2,080	0%	2	42	18	119	2,080	6%
Total	10	190	-	-	-	Total	137	18	-	-	-

5.4.4. Outputs

Before tackling the different decision criteria, two levels of analysis must be defined (see Figure 56): The *global* and *corridor* levels. Outputs at the global level, comprising all 986 TAZs from the MIT-FSM model, do not present substantial changes, as the GLX project is relatively minor when compared to the size of the whole network, therefore, some analysis (e.g. travel times) will be done at the corridor level, covering all TAZs within half-mile from each GLX station.

The TAZs at the corridor level are distributed along 4 towns covering more than 70,000 inhabitants and 34,000 jobs over 10.57 square kilometers (see Table 91).

Clearly Somerville benefits the most from the GLX project. With almost 70% of the served population living in this town and nearly half the jobs, it is here where most of the project sits. Boston, on the other hand, almost does not benefit at all from this project. In fact the GLX project did only consider the 3 towns of Cambridge, Medford and Somerville (Mass DOT, 2016). However, we have decided to keep Boston as part of the corridor level analysis.

<u>*Capital Costs*</u>

To estimate capital costs, the GLX project (MBTA & Mass DOT, 2010; 5.3) was consulted. Estimations from 2008 reported an LRT capital cost of US$ 103 million/km. The most recent capital cost estimations (2016) for the LRT alternative is US$ 333 million/km, this representing an increase of more than 300%. Estimations from 2008 reported a BRT capital cost of US$ 19 million/km. Considering the same increase rate, the current BRT capital cost estimation should be around US$ 61 million/km.

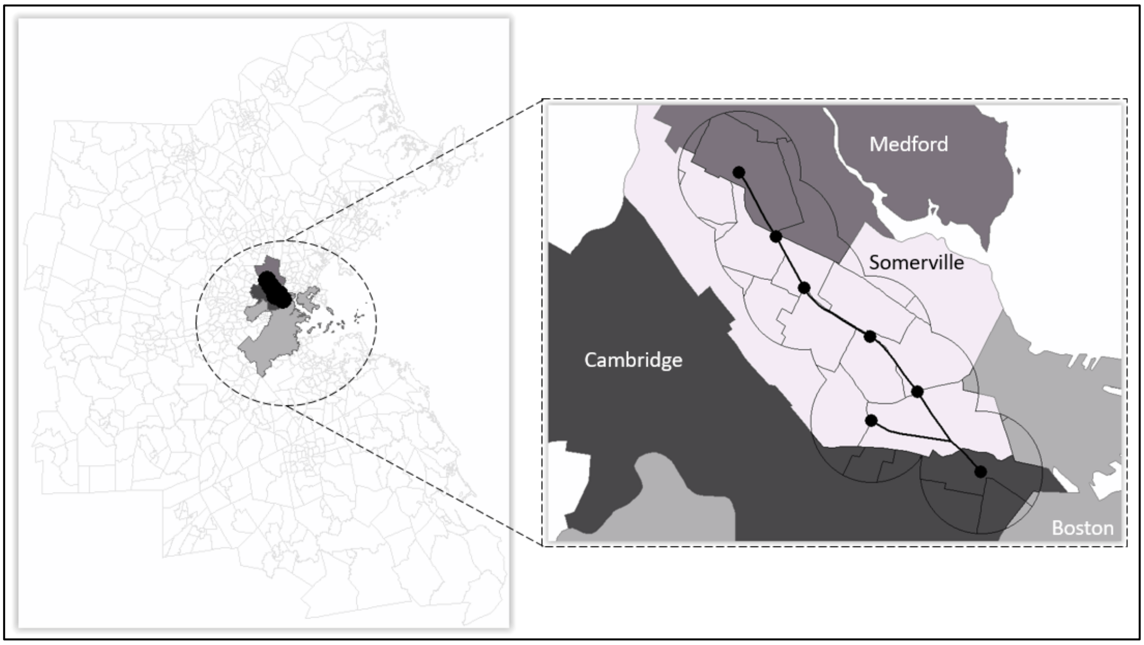

Figure 56 – Global (left) and corridor (right) levels

Table 91 - Data about the corridor level

TAZs	Town	Population	Jobs	% Jobs	Area (km²)	Population Density (hab./km²)	Job Density (Jobs/km²)
1, 11, 85, 86	Boston	587	2,313	80	0.28	2,072	8,261
257, 258, 259, 263, 264, 269	Cambridge	11,088	13,858	56	1.76	6,283	7,874
237, 238, 239	Medford	9,576	2,679	22	1.96	4,863	1,367
242-256	Somerville	49,485	15,220	24	6.56	7,546	2,320
Total		70,710	34,071	33	10.57	6,690	3,223

The No Build alternative will not have any extra capital investment; therefore, it will have zero capital costs (see Table 92).

Table 92 - Capital costs

Alternatives	Capital Cost (M US$/km)
No Build	0
BRT	61
LRT	333

Operating Costs

For the No Build alternative, the operating cost is US$ 0.16 million/year/km. This figure is obtained by dividing US$ 202 million (MBTA's bus budgeted operating costs for FY2016 (MBTA, 2015)) by 1200 km (the total MBTA's bus network length).

According to the GLX project (MBTA & Mass DOT, 2010; 5.3), the estimations in 2008 for the LRT operating costs were US$ 2.7 million/year/km. The most recent operating cost estimations (2016) for the LRT alternative are US$ 3.8 million/year/km, a 141% increase of the initial value. Estimations from 2008 for the BRT reported an operating cost of US$ 1.8 million/year/km. Considering the same 141% increase, current BRT operating cost of US$ 2.5 million/year/km.

As the bus routes 80 and 87, from the No Build alternative, will remain operational on the LRT or BRT alternatives, the No Build operating costs must be added to LRT and BRT operating cost estimations (see Table 93).

Table 93 - Operating costs

Alternatives	Operating Cost (M US$/year/km)
No Build	0.16
BRT	2.66
LRT	3.96

Revenues

This decision criterion refers to daily ridership per km, a proxy for farebox revenues. It is counted as total daily linked trips per km. Table 94 presents the estimated values for 2030.

For NB, ridership is counted on MBTA bus routes 80 and 87, while for the LRT and the BRT alternatives, the new transit services and the same bus routes are counted, as they continue to serve the corridor. In the Table 94, we can see that LRT stands out over BRT and NB, on both branches. One of the big advantages of the LRT alternative is connecting Somerville, without transferring at Lechmere, to the rest of the Green Line.

Table 94 - Revenues

NB	Service	Boardings	Alightings	Total	Length (km)	Revenues
	Bus 80 N (out)	2,214	2,042	4,256	5.9	721
	Bus 80 S (in)	1,195	1,392	2,587	5.9	438
	Bus 87 N (out)	1,503	1,241	2,744	2.4	1,143
	Bus 87 S (in)	185	335	520	1.9	273
	Total	5,096	5,011	10,107	8.1	2,577
	Final Total					2,577
BRT	Bus 80 N (out)	1,038	877	1,914	5.9	324
	Bus 80 S (in)	594	802	1,396	5.9	237
	Bus 87 N (out)	830	599	1,429	2.4	595
	Bus 87 S (in)	226	420	645	1.9	340
	Total	2,688	2,696	5,384	8.1	1,496
	BRT tCollA (out)	4,364	4,364	8,728	5.9	1,479
	BRT tLech (in)	2,984	2,984	5,967	5.9	1,011
	BRT tUnion (out)	857	857	1,713	1.9	902
	BRT tLech (in)	486	486	973	1.9	512
	Total	8,690	8,690	17,381	7.8	3,904
	Final Total					5,400
LRT	Bus 80 N (out)	271	187	457	5.9	78
	Bus 80 S (in)	69	235	304	5.9	52
	Bus 87 N (out)	237	170	406	2.4	169
	Bus 87 S (in)	18	57	76	1.9	40
	Total	595	649	1,244	8.1	338
	LRT tCollA (out)	2,329	15,112	17,441	5.4	3,230
	LRT tRiv (in)	12,624	1,522	14,146	5.4	2,620
	LRT tUnion (out)	161	2,321	2,482	1.4	1,773
	LRT tHeath (in)	1,949	155	2,104	1.4	1,503
	Total	17,063	19,109	36,172	6.9	9,125
	Final Total					9,463

Note: Total lengths are one-way. “Out” and “In” stand for service going outbound Boston and Inbound Boston.

Average transit travel time

The MIT-FSM model computes AM transit travel time skims (see Appendix). From this data, a weighted average is computed by considering transit O/D home-based work matrices, producing travel times, for the horizon year (2030) at corridor level (Table 95). The LRT alternative is better than the others.

Table 95 - Average transit commute travel time

Alternatives	Travel time (minutes)
NB	34.8
BRT	34.1
LRT	32.3

Non-private motorized mode share

This criterion covers the share of commute to work, made with public transit and walking modes. The MIT-FSM model outputs O/D matrices for AM home-based work trips, divided in 5 modes: auto passenger (APAX), drive to access transit (DAT), single occupancy vehicle (SOV), walking (WALK), and walk to access transit (WAT) (see Appendix). Table 96 presents modes share for the horizon year (2030) at corridor level.

When considering WALK, WAT and DAT together at corridor level, the changes are not substantial. WAT and DAT modes present, however, an increase in transit use for both BRT and LRT alternatives, when compared with the NB alternative. Surprisingly, what stands out is the decrease in walking (WALK), while the APAX and SOV modes remain stable.

Table 96 - Mode share

Alternatives	APAX + SOV	Total	WALK	WAT + DAT
NB	47.3	52.7	25.1	27.6
BRT	47.0	53.0	24.3	28.7
LRT	47.6	52.4	21.7	30.7

Average transfers per trip

This criterion is not available at corridor level, and will be therefore analyzed at global level. To obtain such indicator total 24-hour transfers were divided by the total of 24-hour O/D transit matrices for the horizon year (2030) at global level (see Appendix). To obtain 24-hour matrices from AM matrices, the parameter of 7.14, drawn from a recent urban mobility survey done in Lisbon Metropolitan Area (MIT Portugal, 2008) was here applied. Table 97 presents the results at global level.

Table 97 - Transfers

Alternatives	Total transfers	Linked trips	Transfers per trip
NB	1,914,935	2,886,071	0.664
BRT	1,914,117	2,894,964	0.661
LRT	1,166,406	2,903,179	0.402

The LRT alternative substantially decreases the number of transfers per trip. One of the major advantages of the rail alternative, when compared to the NB and the BRT, is that it is the only alternative that eliminates the need of transfers at Lechmere, warranting direct one-seat trips from Union Square and College Avenue to Boston city center, and to all E and D Green Line stations. The road-based alternatives will always require a transfer at Lechmere.

Emissions

This criterion covers CO_2 emissions from the vehicles used in each alternative. As the MIT-FSM model does not compute any CO_2 or any other type of greenhouse gas emissions, the same sample of projects used to define market values (FTA, 2010) was used were. The median Bus/BRT and LRT CO_2 emissions of 181 gCO_2/pax.km and 119 gCO2/pax.km, respectively, were adopted for the investment alternatives.

Table 98 – Emissions

Alternatives	CO_2 emissions: g CO_2/pax.km
NB	181
BRT	181
LRT	119

Real estate

To estimate the impacts on real estate caused by new transit service and infrastructure (within half-mile from stations), the land use method applied to the illustrative case study (see Chapter 4) is here replicated. Based on various sources with the dataset previously referred (U.S. Census Bureau and CTPS, 2012), it was possible to know a variety of TAZ indicators from 2010, household density being one of them (see Appendix). Household density is a good proxy for home density, therefore it is employed here. Since many real estate gains tend to occur before or shortly after the system starts operation, we assume that by 2020 most real estate benefits will happen and, by the horizon year (2030), all real estate benefits have happened.

The TAZs within half-mile from stations and their areas were determined (Table 99), and with the household density, we estimated the total number of properties (homes) affected by the project. These figures were then updated for 2020, since the used data is from 2010. To do this, housing demand projections for the BMA (MAPC, 2014) were employed. Finally, with the median home price per square meter for January 2016 (extracted from the same source used to develop market values (Zillow, 2016)), we estimated the total home price. The 2020 home prices were assumed to be the same as in 2016 (see Table 99).

Finally, the potential impact caused by the presence of transit stations on surrounding real estate was computed. The No Build alternative does not have any impact, so the average price per square meter is the total home price divided by the total number of homes. For the BRT and the LRT, the same growth rates employed in the small case study (7.6% (Perk et al., 2013) and 3% (Diao, 2015) respectively) were considered for this estimation (see Table 100).

Table 99 – Home prices (2020)

TAZ	Town	Median home price (US$/m²)	Homes	Total home price (M US$/m²)
1, 11, 85, 86	Boston	6,717	318	2.14
257, 258, 259, 263, 264, 269	Cambridge	4,811	5,333	25.66
237, 238, 239	Medford	3,348	3,368	11.27
242-256	Somerville	4,704	21,307	100.22
Total			32,262	139

The final home prices per square meter are higher than the upper limit. However this was expected since Boston has one of the highest real estate prices (Zillow, 2016) in the US. Per the chosen literature, BRT might promote gains in home values up to 7.6% (Perk et al., 2013) while LRT only 3% (Diao, 2015). Moreover, some authors believe that rail systems and, more specifically, light rail might impact surrounding real estate more than road-based systems (Vuchic, 2007).

Table 100 - Real estate

Alternatives	Home price (US$/m²)
NB	4,593
BRT	4,942
LRT	4,731

Density

To estimate the growth in population density within half-mile from stations, the growth rates suggested by Bocarejo et al. (2013) and Bhattacharjee & Goetz (2016) were used – a population growth up to 10% and 7% at BRT and LRT station areas, respectively. Since many of population changes tend to occur before or shortly after the system starts operation, we assume that by 2020 most changes will happen, and, by the horizon year (2030), all changes will have happened. To estimate 2020 population based on the available data (2010), the population demand projections for the BMA (MAPC, 2014) are here used (see Table 101).

Table 101 – Population density (2020)

TAZ	Town	Population	Area (km²)	Population density (hab./km²)
1, 11, 85, 86	Boston	610	0.28	2,150
257, 258, 259, 263, 264, 269	Cambridge	11,373	1.76	6,445
237, 238, 239	Medford	9,768	1.96	4,974
242-256	Somerville	53,445	6.56	8,150
Total		75,196	10.57	7,114

Table 102 presents the final figures for the density, after applying the growth rates.

Table 102 - Population density growth

Alternatives	Population density (hab./km^2)
NB	7,114
BRT	7,826
LRT	7,612

All alternatives present high population densities when compared with the market values. As stated before, the city of Somerville, where the project mainly sits, is one of the densest cities of America and the densest city of Massachusetts (Mass DOT, 2016).

Mixed-use

The mixed-use criterion is estimated using the entropy index (Cervero and Kockelman, 1997), varying between 0 and 1, where 0 means complete homogeneity (only jobs or only population), and 1 means heterogeneity (jobs and population evenly distributed).

Again here, we have used empirical findings from the literature. Regarding job and population growth, the literature lacks quantitative empirical studies, being mainly either qualitative or oriented towards land uses and not population or jobs: it is common to estimate growth in new apartments and retail activities (Badoe and Miller, 2000; Cervero and Kang, 2011; Deng and Nelson, 2010) but not growth in residents or workers. However, Bocarejo et al. (2013) and Bhattacharjee & Goetz (2016) report a population growth up to 10% and 7% at BRT and LRT station areas, respectively. Kang (2010) and Banister & Thurstain-Goodwin (2011) report an employment growth up to 50% and 17% at BRT and LRT station areas, respectively.

Since most job and population changes tend to occur before or shortly after the system starts operation, we assume that by 2020 most changes will happen, and, by the horizon year (2030), all changes will have happened. To estimate 2020 population and jobs based on the available 2010 database, population and jobs demand projections for the BMA (MAPC, 2014; MPO, 2015) are here used (see Table 103).

Table 104 presents the values computed for the entropy index, in our case.

The final figures are very close to 1, this meaning that the station areas, overall, have a balanced distribution of land uses.

Table 103 - Population and jobs (2020)

TAZ	Town	Population	Jobs	% Jobs
1, 11, 85, 86	Boston	610	2,384	80
257, 258, 259, 263, 264, 269	Cambridge	11,373	14,285	56
237, 238, 239	Medford	9,768	2,762	22
242-256	Somerville	53,445	15,689	23
Total		75,196	35,120	32

Table 104 - Entropy index

Alternatives	Entropy Index
NB	0.90
BRT	0.96
LRT	0.92

Accessibility

The accessibility criterion is measured by the share of jobs reachable by transit within 60 minutes. The MIT-FSM model outputs AM transit travel time skims and AM home-based work O/D matrices (see Appendix). With these matrices, accessibility is estimated by checking which transit home-based work trips, for each O/D pair, take no longer than 60 minutes to reach destination. The number of transit trips is then divided by the total number of trips, resulting in a percentage. This procedure is developed for the corridor level (Table 105).

Table 105 - Accessibility by transit

Alternatives	Accessibility (%)
NB	26
BRT	27
LRT	29

More trips reach destination, within 60 minutes, with the LRT than with the other alternatives. One of the major advantages of the rail alternative, when compared to NB and BRT, is that it is the only alternative with no need of transfers at Lechmere, thus speeding up travel times and increasing accessibility to work levels.

5.4.5. Value functions

All the computed values are now summarized in Table 106.

Since the different criteria have different measurement units (e.g. costs in monetary units, travel time in minutes, emissions in tons) to write down the value functions we need to normalize the values to a same scale. The natural way to do it consists in setting a scale from 0 to 1, normally using market values, whereas 0 represents the lower bound / worst case, and 1 the upper bound

/ best case. This scale can take multiple patterns, and in this study a linear pattern was used. Such patterns might be defined with the help of the decision-maker, and might be non-linear. This would mean that some “differences” in the values (this might lead to an exponential pattern) will have more importance than others. Table 107 shows the normalized results (generated from the previous table).

Table 106 - The outputs

Criterion	Subcriterion	NB	BRT	LRT
Finance	Capital costs (M US$/km)	0.0	61.0	333.0
	Operating costs (M US$/year/km)	0.16	2.66	3.96
	Revenues (trips/day/km)	2,577	5,400	9,463
Transport	Travel time (minutes)	34.8	34.1	32.3
	Mode share (%)	53	53	52
	Transfers	0.66	0.66	0.40
	CO_2 emissions (g/pax.km)	181	181	119
Land use	Real estate (US$/m^2)	4,593	4,942	4,731
	Density (pop/km^2)	7,114	7,826	7,612
	Mixed-use (entropy)	90	96	92
	Accessibility (%)	26	27	29

Table 107 – Normalized results

Criterion	Subcriterion	NB	BRT	LRT		Market Values	
						Best	Worst
Finance	Capital costs (M US$/km)	1.08	0.07	-4.47		5	65
	Operating costs (M US$/year/km)	1.05	-2.08	-3.70		0.2	1
	Revenues (trips/day/km)	0.20	0.71	1.45		7 000	1 500
Transport	Travel time (minutes)	-0.24	-0.21	-0.12		10	30
	Mode share (%)	4.77	4.80	4.74		15	5
	Transfers	0.78	0.78	0.87		0	3
	CO_2 emissions (g/pax.km)	0.19	0.19	0.81		100	200
Land use	Real estate (US$/m^2)	1.80	1.97	1.87		2622	874
	Density (pop/km^2)	3.74	4.22	4.07		3000	1500
	Mixed-use (entropy)	1.00	1.30	1.10		90	70
	Accessibility (%)	2.10	2.20	2.40		15	5

Some figures surpass lower or upper thresholds. This is not an issue since the thresholds are built using a sample of market values and are just a guidance. As referred in 4.6.2.5, the normalized values above 1 or below 0 could be removed with new market values. However, changing the market values would require changing the weights in the expert’s priority profile accordingly as well, so the distances between the final scores would remain the same – a linear transformation would occur.

When the experts answered the survey, they explicitly compared variations considering the market values adopted in this work, hence their answers strictly reflect *that interval and not any other interval.* Therefore, with new market values, new weights would have to be computed. This procedure would eliminate those somewhat strange normalized values) and change the values of the final scores, however it would not the choice nor the ranking.

5.4.6. Experts' priority profile

Table 108 presents the experts' priority profile resulting from the interviews carried out with selected experts. This survey was carried out independently from this specific decision problem, i.e. the experts did not know it was to be employed on the GLX project. In that way, it is possible to avoid the so-called "optimism bias" (Pickrell, 1992) towards one investment alternative over another.

Table 108 - Experts' priority profile

Criteria	Subcriteria	Final weights	Equivalent weights	Order of priority
Finance		27.3%		
	Capital costs	21.7%	5.9%	9th
	Operating costs	33.0%	9.0%	4th
	Revenues	45.3%	12.4%	2nd
Transport		52.4%		
	Travel time	42.7%	22.4%	1st
	Mode share	23.5%	12.3%	3rd
	Transfers	17.0%	8.9%	5th
	Emissions	16.8%	8.8%	6th
Land use		20.2%		
	Real estate	18.1%	3.7%	10th
	Density	31.3%	6.3%	8th
	Mixed-use	15.7%	3.2%	11th
	Accessibility	34.9%	7.1%	7th

5.4.7. Choice and Ranking

Table 109 presents the final choice and ranking obtained by applying the experts' priority profile to the value functions. The final ranking is No Build, BRT and LRT.

This ranking is the opposite of that of the GLX project (Mass DOT, 2016) (which has considered a similar BRT alternative, but has rather decided for the LRT alternative). Choosing the LRT is the "obvious" option, otherwise the project would not be called "Green Line extension". By looking at the criteria of finance, transport and land use, the LRT substantially underperforms on the first one, being the best on transport and the second best on land use. High capital and operating costs diminish the potential gains from the project. The BRT and LRT benefits are possibly not enough to justify their choice.

Table 109 - Choice and Ranking.

Ranking	Investment alternative	Criteria scores			Final score
		Finance	Transport	Land use	
1st	No Build	0.18	0.62	0.48	1.29
2nd	BRT	-0.10	0.63	0.54	1.07
3rd	LRT	-0.42	0.71	0.53	0.82

5.4.8. Sensitivity analysis

The outputs produced by the MIT-FSM model and other auxiliary methods clearly provide interesting guidelines, but are subject to various types of uncertainty. In these types of projects, it is common to underestimate costs and overestimate ridership, and therefore the results should be taken very carefully. It is then important to see how much the model outputs can change their values and how sound is the final ranking of the alternatives. For this purpose, we perform here some sensitivity and risk analyses. These analyses test the robustness of the alternatives, and simulate endogenous and exogenous uncertainty scenarios.

5.4.8.1. Uncertainty in the modeling process and inputs

Following the approach presented in chapter 4, several uncertainty scenarios are tested: a first group of first scenarios, that affect all investment alternatives equally, and two other groups of more specific scenarios with specific probabilities assigned to each investment alternative. Overall, all procedures try to answer the following question:

What changes in the modeling process and inputs would lead to changes in the ranking of the alternatives?

The first group of scenarios are listed below:

- Pessimistic “A” (PA): for all investment alternatives, operating costs, travel times and revenues worsen by 30%. Probability: 20%
- Pessimistic “B” (PB): for all investment alternatives, operating costs, travel times and revenues worsen by 10%. Probability: 45%
- Neutral (N): current scenario. Probability: 20%.

- Optimistic "D" (OD): for all investment alternatives, operating costs, travel times and revenues improve by 10%. Probability: 10%
- Optimistic "E" (OE): for all investment alternatives, operating costs, travel times and revenues improve by 30%. Probability: 5%

Table 110, Table 111 and Figure 57 depict the inputs and results for this set of scenarios. The results from the scenarios tested do not change the final ranking, mainly because they act over all investment alternatives, thus degrading or upgrading them altogether.

Table 110 - Inputs to the first set of scenarios

Scenarios	Operating costs (M US$/year/km)			Revenues (trips/day/km)			Travel time (min)		
	NB	BRT	LRT	NB	BRT	LRT	NB	BRT	LRT
PA	0.20	3.46	5.15	1,804	3,780	6,624	45.2	44.3	42.0
PB	0.17	2.93	4.36	2,319	4,860	8,517	38.3	37.5	35.5
N	0.16	2.66	3.96	2,577	5,400	9,463	34.8	34.1	32.3
OD	0.14	2.39	3.56	2,835	5,940	10,409	31.3	30.7	29.1
OE	0.11	1.86	2.77	3,350	7,020	12,302	24.4	23.9	22.6

Table 111 - Results from the first set of scenarios

Scenarios		NB	BRT	LRT
PA (p =20%)	Scores	1.06	0.74	0.42
	Ranking	1^{st}	2^{nd}	3^{rd}
PB (p = 45%)	Scores	1.15	0.90	0.62
	Ranking	1^{st}	2^{nd}	3^{rd}
N (p = 20%)	Scores	1.20	0.98	0.72
	Ranking	1^{st}	2^{nd}	3^{rd}
OD (p = 10%)	Scores	1.25	1.06	0.83
	Ranking	1^{st}	2^{nd}	3^{rd}
OE (p = 5%)	Scores	1.34	1.22	1.03
	Ranking	1^{st}	2^{nd}	3^{rd}
Expected score		1.16	0.92	0.64
Worst score		1.06	0.74	0.42

Another set of scenarios was tested based on the 2016 MBTA reliability data (MBTA, 2017): 40%, 17% and 29% of MBTA buses, BRTs and LRTs were not on time, respectively. With this information, we have built two travel time uncertainty scenarios (Table 112, Table 113 and Figure 58): one considering a delay (Delay scenario), and another considering the current travel time estimations (Neutral scenario). In the absence of better data, a typical delay could take up to five minutes. In these two scenarios, NB remains the chosen alternative.

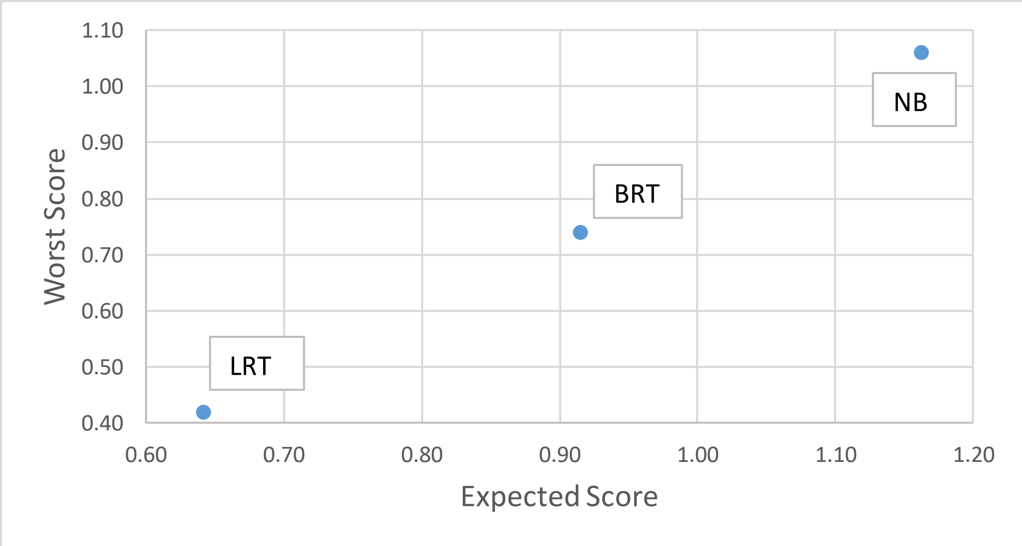

Figure 57 - Results from the first set of scenarios

Table 112 - Inputs to the reliability set of scenarios

Delay scenario	NB (p=40%)	BRT (p=17%)	LRT (p=29%)
	39.8 min.	39.1 min.	37.3 min.
Neutral scenario	NB (p=60%)	BRT (p=83%)	LRT (p=71%)
	34.8 min.	34.1 min.	32.3 min.

Table 113 - Results from the reliability set of scenarios

Scenarios		**NB**	**BRT**	**LRT**
Delay	Scores	1.14	0.92	0.67
	Ranking	1st	2nd	3rd
Neutral	Scores	1.20	0.98	0.72
	Ranking	1st	2nd	3rd
Expected score		1.18	0.97	0.71
Worst score		1.14	0.92	0.67

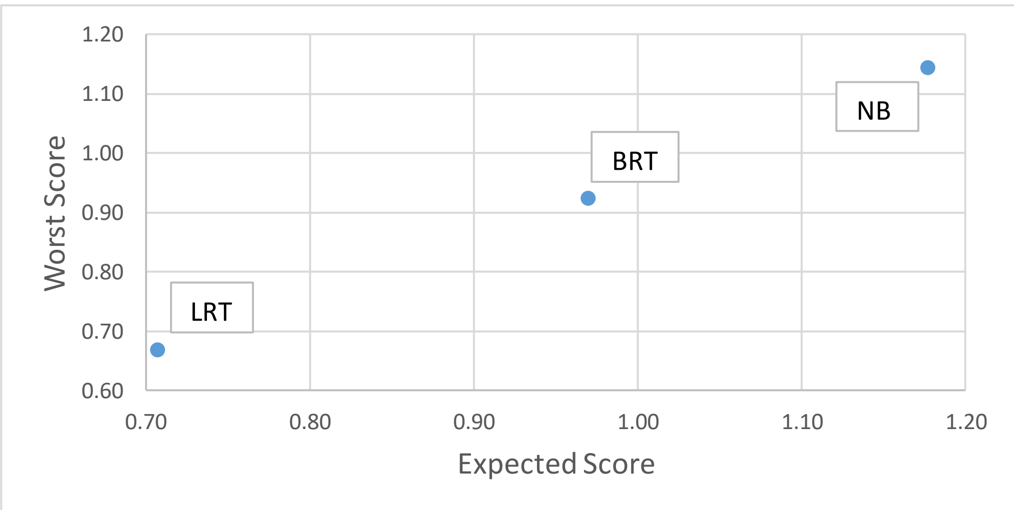

Figure 58 - Results from the reliability set of scenarios

Higgins and Kanaroglou (2016) have recently reviewed forty years of modeling rapid transit's land value uplift in North America, having concluded that LRT's residential property price impacts vary substantially, with about 50% probability of being positive, 25% probability of being none, and 25% probability of being negative. For BRT, it is about a 40% probability of being positive; 40% probability of being none, and 20% probability of being negative. With these information, three real estate uncertainty scenarios were assembled (Table 114 and Table 115).

For Pessimistic F (PF) scenario, a negative property price impact of 1.5% (the lowest negative impact reported by Higgins and Kanaroglou (2016) for LRT systems), is assigned for LRTs and a negative property price impact of 3% (the lowest negative impact reported by Higgins and Kanaroglou (2016) for BRT systems), is assigned for BRTs. For Pessimistic G (PG) scenario, property value impacts are none and for the Neutral (N) scenario, property value impacts are the current impacts.

Table 114 - Inputs to the real estate set of scenarios

Pessimistic F (PF) scenario	NB (p=0%)	BRT (p=20%)	LRT (p=24.5%)
	4,593 €/m^2	4,455 €/m^2	4,524 €/m^2
Pessimistic G (PG) scenario	NB (p=0%)	BRT (p=40%)	LRT (p=24.6%)
	4,593 €/m^2	4,593 €/m^2	4,593 €/m^2
Neutral (N) scenario	NB (p=100%)	BRT (p=40%)	LRT (p=50.9%)
	4,593 €/m^2	4,942 €/m^2	4,731 €/m^2

Table 115 - Results from the real estate set of scenarios

Scenarios		NB	BRT	LRT
PF	Scores	1.199	0.971	0.720
	Ranking	1st	2nd	3rd
PG	Scores	1.199	0.973	0.721
	Ranking	1st	2nd	3rd
N	Scores	1.199	0.980	0.724
	Ranking	1st	2nd	3rd
Expected score		1.199	0.975	0.722
Worst score		1.199	0.971	0.720

With these analyses, the ranking remains the same, with NB as the chosen alternative.

5.4.8.2. Normalization

How does the normalization process influence the ranking?

Within the normalization process, some assumptions can be discussed and tested, by basically adopting non-linear normalization scales.

A linear function is somewhat a natural normalization approach because it does not demand a thorough study regarding the problem and the decision-maker preferences. Since one of the purposes of this research is to build a flexible DSS, that can be applied to various decision problems without the need of an informed decision-maker, a linear normalization process would meet this purpose. In an exponential normalization scale, the decision-maker favors better results. He tends to value more improvements on subcriteria and, therefore, results closer or above the upper market value limit will highly dictate the final choice. A possibility would be to change from a linear to exponential normalization scales, but no expert was consulted on this possibility. Therefore, we decided to not analyze different normalization processes.

5.4.8.3. Priority profiles

How does the priority profile influence the ranking?

Along with the normalization process, another substantial source of variability is the priority profile. In particular, for the average or the mode of all expert answers (see Table 116 and Table 117).

Table 116 - Average priority profile case

Criteria/Alternatives	**Weights**		**NB**	**BRT**	**LRT**
	Final	**Equivalent**			
Finance	28.5%		0.2	-0.1	-0.5
Capital costs	23.8%	6.8%	0.3	0.0	-1.1
Operating costs	33.3%	9.5%	0.3	-0.7	-1.2
Revenues	42.9%	12.2%	0.1	0.3	0.6
Transport	50.2%		0.6	0.6	0.7
Travel time	39.7%	19.9%	-0.1	-0.1	0.0
Mode share	24.4%	12.2%	1.2	1.2	1.2
Transfers per trip	18.1%	9.1%	0.1	0.1	0.2
Emissions	17.8%	8.9%	0.0	0.0	0.1
Land use	21.3%		0.4	0.5	0.5
Real estate	21.2%	4.5%	0.4	0.4	0.4
Mixed-use	17.6%	3.7%	0,2	0,2	0,2
Density	30.5%	6.5%	1,1	1,3	1,2
Accessibility	30.8%	6.6%	0.6	0.7	0.7
Score			1.32	1.09	0.78
Ranking			1st	2nd	3rd

Table 117 - Mode priority profile case

Criteria/Alternatives	Weights		NB	BRT	LRT
	Final	Equivalent			
Finance	29.5%		0.2	-0.2	-0.6
Capital costs	10.3%	3.1%	0.1	0.0	-0.5
Operating costs	52.9%	15.6%	0.6	-1.1	-2.0
Revenues	36.8%	10.9%	0.1	0.3	0.5
Transport	54.5%		0.3	0.3	0.4
Travel time	72.4%	39.5%	-0.2	-0.1	-0.1
Mode share	14.9%	8.2%	0.7	0.7	0.7
Transfers per trip	6.9%	3.8%	0.1	0.1	0.1
Emissions	5.7%	3.1%	0.0	0.0	0.0
Land use	15.9%		0.4	0.4	0.4
Real estate	8.6%	1.4%	0.2	0.2	0.2
Mixed-use	26.9%	4.3%	0.3	0.3	0.3
Density	32.3%	5.1%	1.2	1.4	1.3
Accessibility	32.3%	5.1%	0.7	0.7	0.8
Score			0.91	0.51	0.25
Ranking			1st	2nd	3rd

Although there are substantial changes on the weights and scores, the rankings remain on both cases. Others plausible cases for the priority profile that somewhat reflect exogenous market or policy pressures are, for instance, a *transit user* case (Table 118).

Similar analyses were performed for a *financial-constrained* case, and an *urban-friendly* case (see analysis in chapter 4). From the three cases, all of them change the scores and the urban-friendly case changes the final ranking, with BRT as the chosen alternative, followed by NB and LRT.

5.4.9. Final choice and ranking

From the scenarios with probability analyzed, none of them changed the final choice. NB remains the best alternative. Since we did not analyze scenarios without probabilities, the preferable alternative remains No Build.

5.5. Conclusions

This chapter describes the real-life case study that we have used to validate and assess the methodology developed in this research project, and to test the DSS designed to support that methodology. This case was developed around the GLX project in the Boston Metropolitan Area (BMA),

Table 118 - Transit user case

Criteria/Alternatives	Weights		NB	BRT	LRT
	Final	**Equivalent**			
Finance	15%		0.1	-0.1	-0.2
Capital costs	21.7%	3.3%	0.2	0.0	-1.0
Operating costs	33.0%	5.0%	0.3	-0.7	-1.2
Revenues	45.3%	6.8%	0.1	0.3	0.7
Transport	70%		0.8	0.8	0.9
Travel time	42.7%	29.9%	-0.1	-0.1	0.0
Mode share	23.5%	16.5%	1.1	1.1	1.1
Transfers per trip	17.0%	11.9%	0.1	0.1	0.1
Emissions	16.8%	11.8%	0.0	0.0	0.1
Land use	15%		0.4	0.4	0.4
Real estate	18.1%	2.7%	0.3	0.4	0.3
Mixed-use	15.7%	2.4%	0.2	0.2	0.2
Density	31.3%	4.7%	1.2	1.3	1.3
Accessibility	34.9%	5.2%	0.7	0.8	0.8
Score			1.29	1.19	1.11
Ranking			1st	2nd	3rd

The BMA is one of the most populated US metropolitan areas, with an extensive and integrated transit system managed by MBTA. MBTA's rail network, also known as the "T", is expanding beyond Lechmere, current terminus for the Green Line service in Cambridge. This expansion, also known as the "GLX" project, will mainly serve Somerville, the densest city in Massachusetts.

The decision-making process and infrastructure construction period have been lengthy and with a lot of uncertainty, largely due to capital costs misestimations. The process started in 2005, with service estimated to commence in 2022. In the beginning, a set of investment alternatives were proposed (including a BRT), but extending the current LRT network was the chosen investment. These alternatives were analyzed with our DSS. The DSS was successfully tested in the case study, showing it is a viable methodological tool, useful to aid decision-makers on similar issues.

The No Build alternative covers an area with just two bus routes, which is questionable since at least one more route, MBTA 85, serves the region. However, only routes 80 and 87 run along the same corridors and would bear most of the impact caused by the project.

The BRT alternative follows the same paths as the routes 80 and 87, while the LRT will run in existing commuter rail ROW. The BRT and LRT systems in the BMA (Silver Line and Green Line respectively) have very few off-boarding payment stations and stops, and almost no traffic prioritization at intersections, partially leading to overall low level of service. These two medium-capacity services were used, in this chapter, for modeling the BRT and LRT investment alternatives.

The MIT-FSM model was of significant help for this case study. With an accurate representation of current mobility conditions in the BMA, the model was flexible enough to allow testing the investment alternatives. Some of the model outputs were not ready for being directly used, but overall, we might say that the MIT-FSM model successfully contributed for this work.

The definition of a corridor level analysis area was essential for accurately quantifying the impacts caused by each alternative. The MIT-FSM model covers a very wide network at the global level, thus performing the analysis at this level would not properly reflect all the changes caused by investment alternatives. The half-mile radius around transit stations precisely covers the TAZs that were most impacted by the investments.

The LRT capital and operating costs were drawn from the GLX project estimations, submitted for FTA funding. The procedure is questionable, since the rest of criteria were estimated by us, following a different methodology, possibly leading to over or underestimating costs. The No Build capital costs were considered to be zero, as no extra capital investment will be done by MBTA on the corridor.

The revenue figures found for the different alternatives show the superiority of the LRT alternative. The average travel time did also improve with the BRT and LRT alternatives. However this improvement is rather small, when compared with that of the GLX project submitted to FTA funding (Mass DOT, 2016) which estimated substantial travel time gains for the LRT alternative (up to 19 minutes). This discrepancy comes mainly from the fact that MBTA estimated station-to-station travel time while we have estimated door-to-door travel time. Moreover, the mode share figures were substantially higher than the market value upper limit, mainly because the limit was defined at a metropolitan scale rather than at a corridor-wide scale.

The subcriterion for the average transfers per trip was defined at a global scale that, at some degree, does not fully reflect the substantial benefit brought by an LRT alternative to transit users. The need of transferring between vehicles during a commute trip is a major disutility for the passenger. Although the subcriterion could be straightforward defined at a corridor level by simply assigning 1 transfer for No Build, 1 transfer for BRT, and 0 for LRT, this procedure can be considered to be wrong as it views the problem through a supply, rather than demand side. Anyhow, transfer data at corridor level would certainly improve the robustness of the results.

For estimating the emissions subcriterion, we have used external data: the same database used to build market values was consulted. Just like emissions, real estate, mixed-use and density were estimated with the help of the selected literature. This procedure is somehow subjective, because it is strictly based on chosen findings from the literature, thus possibly reflecting the analysts' opinions. On the other hand, for accessibility, we have only used the MIT-FSM results.

The normalization process was based on a linear function, with some clear limitations, that might have been overcome by other options (e.g. by using an exponential function). Moreover, the market values adopted were sometimes too narrow or inadequate for this specific project, thus delivering very high or very low normalized figures. Using the priority profile defined by a set of experts, we could finally deliver a ranking of the alternatives – first, No Build; second, BRT; and LRT as third choice.

An extensive sensitivity analysis was performed to check which factors might influence the final ranking and scores, by focusing on potential uncertainty in the modeling process and inputs, variations in the normalization process and in the priority profile. For the uncertainty in modeling process and inputs, travel time, operating costs, revenues and real estate were analyzed. Issues related to the normalization process and the priority profile were also addressed within the sensitivity analysis.

This comprehensive sensitivity analysis confirmed the above findings and showed how robust the ranking is, with the No Build alternative being the first.

6. CONCLUSIONS AND FURTHER RESEARCH

- Introduction
- Conclusions on the methodological approach
- Conclusions on the literature review
- Conclusions on the Decision Support System
- Conclusions on the case study
- Strengths and shortcomings of the research and proposals for future work

6.1. Introduction

This PhD thesis discussed several subjects regarding the decision-making processes that are typically carried out in contexts of capital investments for public transport. The thesis also presents a methodology to support these processes, and a structured DSS that aims at helping decision-makers when having to choose a public transport investment alternative from a set of alternatives. The DSS was then tested twice: in a small illustrative case study, and in a real decision problem, the Green Line Extension Project in the Boston Metropolitan Area. These experiments clearly show the potential of the developed tools, and highlight the contributions of our framework. This chapter summarizes these contributions and presents some directions for further research.

6.2. Conclusions on the methodological approach

6.2.1. The emergence of the topic

Decision-making processes in public transportation can have a variety of configurations. When dealing with allocating scarce public funds for building or upgrading a transit system, several decision aspects should be taken into consideration during the decision-making process, thus demanding a holistic approach that covers multiple issues. With restricted budgets and under an environmentally-constrained setting, it is paramount that transportation systems and land use are considered together, thus ensuring higher sustainability levels.

Changes in land use brought by new transportation services or infrastructure, typically happening near stations, are not adequately covered in decision-making processes, mainly because they are hard to monetize to fit in a CBA. These benefits are frequently seen as value transfer instead of value creation, and they are too complex to be assessed by traditional transport modeling software. Gains in accessibility, density, mixed-use and property values are some impacts of transportation services that reflect changes in land use, and should be considered when designing or re-designing those services. As covered in chapters 2 and 3, the proximity to transportation stations can increase local accessibility and, therefore, influence the value of surrounding properties and rents, affect population and job density, attract business and services, and spur economic development.

There are several approaches for understanding and handling land use changes, in the context of decision-making processes for transportation systems: political/planning approaches (value capture mechanisms, Transit Oriented Development (TOD) plans); and methodological / modeling approaches (Land Use and Transport (LUT) models, or evaluation at face values).

Value capture mechanisms can be difficult to use, as they demand some articulation between different stakeholders to guarantee their application, and TOD plans can be hard to implement, as responsibilities and decision-making processes are fragmented. LUT models are also challenging, as they are rather sophisticated, data intensive, and expensive to build and to keep updated. Hence, a new decision support system, incorporating land use changes, not requiring TOD plans, value capture mechanisms or sophisticated LUT models, may be quite valuable in practical terms. The current lack of decision support methodologies, and tools, that incorporate land use changes, along with more traditional decision aspects, clearly justifies the research of this doctoral project.

6.2.2. The research methodology

The research methodology was defined by first defining the research questions and objectives, and was structured along three major lines: *Observe*, *Understand* and *Intervene*. In the first line, a thorough literature review was performed, covering many aspects related to the topic of public transport decision-making processes and land use. This allowed us to better structure the next developments of the research, by providing a solid base of knowledge to work over (chapters 2 and 3). Along the *Understand* line, the DSS was developed (chapter 4), and tested on a small illustrative problem (chapter 4) and on a real case study (chapter 5). Finally, in the *Intervene* line, the final version of the thesis and the DSS prototype were delivered. The approach adopted proved successful in structuring the research, thus helping to deliver a comprehensive doctoral dissertation.

6.2.3. The objectives and the research questions

The objectives defined for this doctoral project were the following (chapter 1):

1. understand current decision-making processes focusing on, but not limiting to, BRT and LRT systems;
2. understand the impacts of transit systems on land use and accessibility;
3. measure these impacts; and
4. consider those impacts in the relevant decision-making processes.

Objective 1 and 2 were addressed in chapters 2 and 3, respectively. In chapter 2, a thorough literature review about current decision-making processes and medium capacity systems (i.e. BRT and LRT) was performed, allowing to understand how such processes work.

In chapter 3, a review of the relation of land use, transit systems and decision-making allowed to understand how transit systems affect land use and accessibility. Measuring the impacts that transit systems, typically within half-mile from stations, have on population, jobs and residential property prices (objective 3), can be done with specific models, such as land use and transport models and hedonic models. However, considering that the complexity associated with modeling and forecasting land use changes is a major reason for overlooking these aspects on decision-making, an efficient model was proposed to overcome this issue, thus addressing objective 4.

The research questions resulted naturally from a comprehensive literature review and the identification of a set of relevant gaps.

Question 1: Have BRT and LRT some impact on accessibility, land use, density and land value that can be measured?

Answer: Yes. The literature review (chapters 2 and 3) provide abundant empirical evidence, typically based on hedonic models and cross-sectional and longitudinal data for measuring impact, showing that BRT and LRT systems might impact, positively and seldom negatively, land use, mainly within half-mile from transit stations.

- **1.1**: Are those impacts mostly benefits rather than costs?
- **Answer:** Yes, they are (see chapter 3). When combined (typically under a TOD plan), increase in density and in the mix of land uses can greatly influence transit use and reduce trip lengths. In very dense cities the modal share of transit trips is substantially higher, when compared with low-density cities. With higher densities transit ridership increases, making public transport more financially viable. Moreover, mixed-use can shorten shopping, leisure and school trips, which can be done by walking or by cycling, thus diminishing car appeal and increasing sustainability. By increasing the mix of uses, origins and destinations are more efficiently distributed (thus diminishing trip loads on traditional suburb-to-CBD corridors and dispersing trips throughout the city). The increase of land values might help finance the transit system, by applying value capture mechanisms. On the other hand, some municipalities are not interested in seeing an increase in prices and rents and rather prefer avoiding what is called gentrification. This type of process can

compromise community sustainability and equity. Such concerns are incorporated in the FTA's decision process that prioritizes projects ensuring affordable housing along the corridor. Finally, accessibility is always seen as a benefit, since better spatial and temporal coverage of transit systems and services can greatly reduce travel times, thus increasing accessibility levels to jobs, healthcare, schools, or leisure.

- **1.2**: Can those benefits and costs help decision-making?
- **Answer:** Yes, they can. Government agencies already employ some sort of land use indicators into their decision-making processes (e.g. FTA). Based on the responses collected from the experts, our research found out that the "land use" criterion got 20% of the total importance, whereas the "transport" criterion got almost 53%, and the "finance" criterion got 27%. Within the "land use" criterion, accessibility, density, real estate and mixed-use subcriteria, got 34.9%, 31.3%, 18.1% and 15.7%, respectively (7^{th}, 8^{th}, 10^{th} and 11^{th} positions in the total ranking of subcriteria). Nevertheless, these subcriteria seem to play a key role in the decision-making process, and should therefore be properly considered.

- **1.3**: Can those benefits (mainly density increase and land use mixture increase) induce medium and long-term ridership?
- **Answer**: To answer this question an integrated LUT model would be necessary. However, in a simple theoretical exercise using our small illustrative case study, density and mixed-use would increase according to the population growth indicators of 10% for the BRT, and 7% for the LRT, and jobs growth indicators of 50% for the BRT and 17% for the LRT. These new households and jobs would generate more trips and, hence, induce transit ridership.

- **1.4**: Could this "induced ridership" be considered during decision-making as a qualitative criterion or as part of passenger forecasts?
- **Answer:** It could be considered in two ways: qualitatively, as in the DSS developed in this work, or as new passengers, this requiring a complete integrated LUT model.

Question 2: How can this knowledge help decision-making? Is it worth considering those benefits during the decision-making process, or the more traditional benefits (travel time and traffic reduction) are enough?

Answer: As reported by the experts on the survey (see above), land use issues seem to play a key role on the decision-making process and should therefore be properly considered.

Question 3: What means the sense of permanence?

Answer: The sense of permanence is the feeling of trust perceived by the different stakeholders (e.g. transit users, business owners) when faced with a transit ROW with a good transit service associated. Rail tracks deployed over the countryside, or in an urban environment, bring a sense of permanence and some certainty about a potential transportation service running on that infrastructure. Differently, transit systems without strong ROW, or of inferior quality and lacking passenger information, can give a sense of uncertainty, rather than permanence.

Question 4: Can we achieve a sense of permanence, and its associated benefits, with road service or only with rail service?

Answer: Yes, we can, Rail systems are very expensive, hence there is typically more commitment from the government to provide a good service (Salvucci, 2015). Buses are easier to change, as they are more flexible (Vuchic, 2007). Moreover, rail mileage is always smaller than bus mileage or road mileage (i.e. fewer stations, fewer lines and smaller system coverage), and therefore can attract more development interest on those key high-accessibility points. The same public perception may not happen with a BRT because it can be easily downgraded or associated with the traditional and ubiquitous bus system. This flexibility can therefore move away potential developments, mainly when politicians are not fully committed in building and maintaining BRT ROW. However, when a strong ROW is secured, typically with the deployment of a good BRT service, a sense of permanence can be achieved. Hence, the transit infrastructure alone (i.e. rail tracks) is not enough if not accompanied with good and reliable rapid transit service. It is not the transit "hardware", steel wheel trains or rubber-tire buses, that influences changes on property and land use, but rather a good service with competitive travel time savings.

6.3. Conclusions on the literature review

Current capital investment decision-making on public transport systems incorporates a variety of aspects, techniques and models. In what concerns the definition of the alternatives to be analyzed, our research focused on BRT and LRT solutions. BRT emerged as a cost-effective alternative for rail-based systems and have considerably evolved, integrating new features and solutions. In general, BRT and LRT are having a growing role in the future of cities.

In what concerns decision processes, the following aspects are typically considered: capital costs, operating costs, revenues / ridership, travel time, reliability, journey quality, comfort and crowding, safety, fitness and health and environment. Capital and operating costs tend to deviate from the estimated values, typically overrunning. Revenue (or ridership), is naturally an important criterion to be considered in decision-making processes. Reduction of travel time is also an important direct benefit of a project, and is somewhat easy to be translated in monetary terms, and thus to be incorporated in a CBA.

When it comes to estimation and forecasting techniques, the four-step model stands out as a popular methodology for computing the impacts the investment alternatives have on selected variables. In this context, CBA and MCDA are two evaluation methodologies that can work separately or in an integrated way. While CBA monetizes all costs and benefits (producing Benefit Cost Ratios, Internal Rates of Return, or Net Present Values), MCDA uses weights, for the different criteria, to come up with a score for each project. Both methodologies have advantages and drawbacks and can work alone, or be combined in some way.

Current capital investment decision-making processes present strong limitations in terms of decision parameters and variables, which are rather hard to quantify, estimate and evaluate. Changes in land use patterns induced by transit investment are very hard to monetize, but they cannot be ignored at all. Another reason for overlooking those factors relies on the difficulty of forecasting or estimating their values.

In fact, forecasting land use changes is a complex procedure that demands sophisticated models and methods. This might be one of the reasons for seldom employing land use changes on transit decision-making. Moreover, land use changes caused by transit investment carry considerable uncertainty (specially concerning property prices), and they are hard to monetize and evaluate. Nonetheless some tools for tackling those issues were discussed in this work (TOD plans and value capture mechanisms).

In this context, it is clear that further research is needed on how to incorporate land use changes on transit decision-making, without requiring demand TOD plans, value capture mechanisms or sophisticated LUT models.

6.4. Conclusions on the Decision Support System

The DSS developed in this work combines an efficient LUT model and a MCDA model, aiming at incorporating land use issues in decision-making, in an innovative and practically relevant approach.

The adoption of MCDA also allowed the development of a hierarchical structure relating criteria and subcriteria, value functions for each alternative and weights resulting from a survey to experts in the domain. For the construction of value functions and the survey, market values of American public transport projects were used. The survey and its results are also another asset of this work, that can be adapted to other decision-making processes in the public transport sector.

On step one of the decision process, the investment alternatives are defined to later go through step two, the efficient LUT model, which has two sub-models: a traditional four-step model and an efficient land use model, that incorporates, from literature, growth indicators of property prices, population and jobs observed at station areas, i.e. within ½-mile of transit stations. After that, a capacity check is performed before advancing to the evaluation process. Value functions are then assembled for each investment alternative, incorporating the normalized results from the LUT model and the expert's priority profile. Value functions will then yield a score for each investment alternative, allowing ranking and deciding. Before finishing the process and adopting a choice, a systematic sensitivity analysis is performed.

The adoption of growth indicators from the literature for the land use model carry some uncertainty, more specifically on the population and job indicators. As referred, there is a scarcity of empirical evidence linking increase in population and jobs, at station areas, triggered by transit investment, hence a broader sample of empirical findings is preferable to assign growth indicators. On the contrary, residential property price growth indicators are more abundant on literature.

Assembling the value functions also results from several assumptions made by us, starting with market values. The market values reflect recent transit and transport indicators, whereas the choice of sources and samples selected were our responsibility. In a real decision problem, this process would have inputs from experts and the decision-maker. Another source of reservation is the survey and its results. Some of those issues were addressed in the sensitivity analysis. In this step, it is possible to test several scenarios considering issues related to induced traffic or changes in land use and transport patterns during the project lifespan, e.g., the score of one alternative might differ from the horizon year to another year, thus, this new score and ranking, may help justify a different choice of investment alternative. The sensitivity analysis gives also room for the analyst and decision-maker to process a “classical” risk analysis.

The small case study used in this work replicates, in a straightforward way, a real situation, showing the potential of the developed DSS in effectively supporting the decision-making process. This system is intended to support decision-making, and it should not replace the economic and financial assessment of investment alternatives.

6.5. Conclusions on the case study

The decision-making process and infrastructure construction period associated with the GLX project are lengthy and uncertain. In the beginning, a set of investment alternatives were proposed, and extending the current LRT network was the chosen investment. These alternatives were analyzed with the DSS.

The MIT-FSM model was of significant help for this case study. With an accurate representation of current mobility conditions in BMA, the model was flexible enough to allow testing the investment alternatives and gather their outputs. The definition of a corridor level analysis area was essential for accurately quantifying the impacts caused by each alternative. After an extensive sensitivity analysis, the preferable final choice and ranking is No Build in the first place, BRT in the second place and LRT in the third place.

6.6. Strengths and shortcomings of the research and proposals for future work

We believe that the main strength of the methodology and DSS developed in this research results from considering the land use changes caused by public transport infrastructure. Overlooking land use changes might substantially affect the final choice of investment, as those changes can benefit the system in the future, by inducing ridership and, in some cases, by generating extra financial resources through value capture mechanisms. And taking these benefits into account in the decision-making process can be crucial for choosing the best project.

Another strength of the DSS is that it has a comprehensive and easy-to-use framework, allowing the decision-maker benchmark, based on the market values, the projects under appraisal against current projects, and providing information on how experts value each decision aspect. The hierarchical structure of the DSS and the survey framework can also be adapted, to include different criteria and subcriteria. Another important feature of the DSS is a framework for sensitivity analysis.

Some limitations of the developed approach are related to the choice of the growth indicators used in the land use model, the use of MCDA, market values and the weight profile.

The growth indicators may reflect local specificities and be therefore very limited. Moreover, depending on the modeling techniques, assumptions, samples and data, these indicators might not be right for different contexts (e.g. a growth indicator obtained from a sample of multifamily housing should not be used for single-family housing).

In what concerns MCDA for aiding transport decision-making there are problems with a high degree of subjectivity, that may lead to arbitrary decisions (often with a waste of public funds on projects with high weights on criteria that are subjectively estimated or not estimated at all). In our survey, experts had little information about the actual investment alternatives (and this was considered by some of them as a weakness of the survey). Moreover, a very diverse sample of experts, coming from different countries and academic and professional backgrounds, helped mitigate potential sources of uncertainty.

Regarding the market values, an effective way for addressing the potential weaknesses arising from the sample of market values is by choosing recent transit projects and transport indicators, which may lead to a more robust sample of market values.

Further research could also focus on a monitoring tool or an *ex post* validation tool, to periodically measure the values of the criteria and subcriteria. This tool could be used in a more tactical level, helping short/medium term investment decisions, rather than at a strategic level.

Also, subcriteria such as Emissions and Accessibility, could be further explored, in other to cover issues related to the various impacts over the environment, which are not limited to the CO_2 emissions, and the overall Accessibility, e.g., accessibility to schools, hospitals, shopping and leisure. In a revised version of the thesis, these subcriteria could be upgraded to a new criterion, e.g. an “Environment” criterion.

To assemble the DSS, several decision parameters presented in the literature review were ignored. In a revised version of DSS, some of those parameters could be incorporated, e.g. reliability, security and safety.

Finally, another path for future research is about understanding the role and usefulness of a DSS in the final choice. In the case of the GLX, the final choice was somewhat decided *a priori*, due to demands from the Clean Air Act. Hence, running the DSS would only give more understanding on the problem, but would not change the final choice made by the decision-maker.

APPENDIX

A.1. Accessibility

Accessibility data used for the market values. Source: Accessibility Observatory (2014).

Nº.	Area	Jobs reachable by transit within 60 minutes	Total Employment	Share of total Jobs reachable by transit within 60 minutes
1	Atlanta	60,758	2,180,785	3%
2	Austin	35,552	790,961	4%
3	Baltimore	137,863	1,243,101	11%
4	Birmingham	18,621	455,937	4%
5	Boston	259,640	3,402,940	8%
6	Buffalo	65,485	522,212	13%
7	Charlotte	46,710	771,127	6%
8	Chicago	305,915	4,156,582	7%
9	Cincinnati	38,553	951,583	4%
10	Cleveland	70,124	925,055	8%
11	Columbus	58,754	834,633	7%
12	Dallas	94,871	2,864,933	3%
13	Denver	176,300	1,180,703	15%
14	Detroit	55,746	1,712,027	3%
15	Hartford	49,463	560,748	9%
16	Houston	122,352	2,543,501	5%
17	Indianapolis	46,757	813,598	6%
18	Kansas City	43,160	944,847	5%
19	Las Vegas	103,055	799,219	13%
20	Los Angeles	396,020	5,239,396	8%
21	Louisville	45,951	576,300	8%
22	Miami	119,500	2,194,802	5%
23	Milwaukee	129,472	742,523	17%
24	Minneapolis	134,173	1,652,044	8%
25	Nashville	31,371	701,990	4%
26	New Orleans	39,601	454,816	9%
27	New York	1,207,860	8,102,471	15%
28	Orlando	41,315	930,605	4%
29	Philadelphia	195,230	2,690,018	7%
30	Phoenix	105,599	1,652,995	6%
31	Pittsburgh	68,857	1,083,900	6%
32	Portland	145,276	982,307	15%
33	Providence	40,245	828,037	5%
34	Raleigh	35,390	520,476	7%
35	Riverside	32,434	1,470,777	2%
36	Sacramento	84,951	839,857	10%
37	Salt Lake City	129,061	507,658	25%
38	San Antonio	85,084	862,085	10%
39	San Diego	113,365	1,263,188	9%

40	San Francisco	349,072	1,900,319	18%
41	San Jose	188,822	789,455	24%
42	Seattle	182,877	1,538,625	12%
43	St. Louis	70,902	1,261,977	6%
44	Tampa	51,026	1,108,850	5%
45	Virginia Beach	33,006	684,496	5%
46	Washington	335,139	2,647,658	13%

A.2. Emissions

Emissions data used for the market values. Source: FTA (2010).

Nº.	Mode	State	Transit Authority	Kg CO_2/ passenger km
1	LRT	CA	Los Angeles County Metropolitan Transportation Authority	0,0617
2	LRT	CA	San Diego Metropolitan Transit System	0,0411
3	LRT	OR	Tri-County Metropolitan Transportation District of Oregon	0,0600
4	LRT	MA	Massachusetts Bay Transportation Authority	0,0750
5	LRT	TX	Dallas Area Rapid Transit Bi-State Development Agency	0,1505
6	LRT	MO	Bi-State Development Agency Denver Regional Transportation	0,0800
7	LRT	CO	Denver Regional Transportation District	0,1925
8	LRT	CA	San Francisco Municipal Railway Sacramento Regional Transit District	0,0843
9	LRT	CA	Sacramento Regional Transit District New Jersey Transit Corporation	0,0953
10	LRT	NJ	New Jersey Transit Corporation (privately operated)	0,1578
11	LRT	PA	Southeastern Pennsylvania Transportation Authority	0,1570
12	LRT	UT	Utah Transit Authority Metro Transit	0,0733
13	LRT	MN	Metro Transit Santa Clara Valley Transportation	0,1189
14	LRT	CA	Santa Clara Valley Transportation Authority	0,1074
15	LRT	MD	Maryland Transit Administration Port Authority of Allegheny County	0,1767
16	LRT	PA	Port Authority of Allegheny County Metropolitan Transit Authority of	0,3864
17	LRT	TX	Metropolitan Transit Authority of Harris County, Texas	0,0879
18	LRT	OH	The Greater Cleveland Regional Transit Authority	0,2570
19	LRT	NY	Niagara Frontier Transportation Authority	0,1099
20	LRT	NJ	New Jersey Transit Corporation (directly operated)	0,1790

21	LRT	NC	Charlotte Area Transit System New Orleans Regional Transit	0,1110
22	LRT	LA	New Orleans Regional Transit Authority	0,0916
23	LRT	CA	North County Transit District Central Puget Sound Regional Transit	0,1336
24	LRT	WA	Central Puget Sound Regional Transit Authority	0,1158
25	LRT	TN	Memphis Area Transit Authority Hillsborough Area Regional Transit	0,9045
26	LRT	FL	Hillsborough Area Regional Transit Authority	0,3498
27	LRT	WA	King County Department of Transportation - Metro Transit Division	0,3667
28	LRT	AR	Central Arkansas Transit Authority Kenosha Transit	0,5178
29	LRT	WI	Kenosha Transit	1,2024
30	Bus	NY	MTA New York City Transit	0,1590
31	Bus	CA	Los Angeles County Metropolitan Transportation Authority	0,1392
32	Bus	NJ	New Jersey Transit Corporation	0,1452
33	Bus	IL	Chicago Transit Authority	0,1945
34	Bus	PA	Southeastern Pennsylvania Transportation Authority	0,1812
35	Bus	WA	King County Department of Transportation - Metro Transit Division	0,1274
36	Bus	DC	Washington Metropolitan Area Transit Authority	0,2024
37	Bus	FL	Miami-Dade Transit	0,1855
38	Bus	TX	Metropolitan Transit Authority of Harris County, Texas	0,1511
39	Bus	MN	Metro Transit	0,1443
40	Bus	HI	City and County of Honolulu Department of Transportation Services	0,1291
41	Bus	NY	MTA Bus Company	0,2694
42	Bus	MD	Maryland Transit Administration	0,1922
43	Bus	CA	Orange County Transportation Authority	0,1607
44	Bus	MA	Massachusetts Bay Transportation Authority	0,2063
45	Bus	PA	Port Authority of Allegheny County	0,2024
46	Bus	CO	Denver Regional Transportation District	0,1640
47	Bus	NJ	Academy Lines, Inc.	0,0499
48	Bus	OR	Tri-County Metropolitan Transportation District of Oregon	0,1570
49	Bus	NV	Regional Transportation Commission of Southern Nevada	0,0358
50	Bus	IL	Pace - Suburban Bus Division	0,1592
51	Bus	GA	Metropolitan Atlanta Rapid Transit Authority	0,2204
52	Bus	CA	Alameda-Contra Costa Transit District	0,2114
53	Bus	TX	VIA Metropolitan Transit	0,2066
54	Bus	NJ	Hudson Transit Lines, Inc.	0,0674
55	Bus	TX	Dallas Area Rapid Transit	0,3413
56	Bus	MI	City of Detroit Department of Transportation	0,1843

57	Bus	CA	San Francisco Municipal Railway	0,1855
58	Bus	FL	Broward County Transportation Department	0,1747
59	Bus	UT	Utah Transit Authority	0,1640
60	Bus	OH	The Greater Cleveland Regional Transit Authority	0,1990
61	Bus	NY	MTA Long Island Bus	0,1564
62	Bus	WI	Milwaukee County Transit System	0,1733
63	Bus	FL	Central Florida Regional Transportation Authority	0,1798
64	Bus	WA	Central Puget Sound Regional Transit Authority	0,0922
65	Bus	NY	Westchester County Bee-Line System	0,1533
66	Bus	CO	Denver Regional Transportation District	0,2142
67	Bus	CA	Santa Clara Valley Transportation Authority	0,2060
68	Bus	MO	Bi-State Development Agency	0,2151
69	Bus	OH	Southwest Ohio Regional Transit Authority	0,1607
70	Bus	NJ	Suburban Transit Corporation	0,0812
71	Bus	CA	Foothill Transit	0,2458
72	Bus	TX	Capital Metropolitan Transportation Authority	0,1886
73	Bus	VA	Hampton Roads Transit	0,1821
74	Bus	CA	San Diego Metropolitan Transit System	0,2382
75	Bus	NC	Charlotte Area Transit System	0,2244
76	Bus	PA	Trans-Bridge Lines, Inc.	0,0569
77	Bus	MI	Suburban Mobility Authority for Regional Transportation	0,2142
78	Bus	MD	Ride-On Montgomery County Transit	0,2080
79	Bus	CA	Long Beach Transit	0,1722

A.3. Capital cost, Revenues, Operating cost, Density and Mixed-use

Capital cost, Revenues, Operating cost, Density and Mixed-use data used for the market values. Source: FTA (2016a).

№.	Mode	Project Name	City	State	Length (miles)	New Stations	Station Distance	Capital cost (M US$)	Operating cost (M US$/year)	Current Daily Ridership	Future Daily Ridership
1	LRT	South Central LRT Extension	Phoenix	AZ	5	7	0.714	498.75	-	-	-
2	LRT	Regional Connector Transit Corridor	Los Angeles	CA	1.9	3	0.633	1,402.93	-	58,580	100,980
3	LRT	Third Street Light Rail Phase 2 - Central Subway	San Francisco	CA	1.7	4	0.425	1,578.30	-	-	35,000
4	BRT	Van Ness Avenue BRT	San Francisco	CA	2	9	0.222	162.81	27	-	52,400
5	BRT	El Camino Real Corridor BRT Project	San Jose	CA	17.4	14	1.243	188.00	-	-	-
6	LRT	Southeast Rail Extension	Denver	CO	2.3	3	0.767	223.58	4.14	4,400	6,600
7	BRT	First Coast Flyer East Corridor BRT	Jacksonville	FL	18.5	21	0.881	33.86	3.34	3,700	
8	BRT	First Coast Flyer Southwest Corridor BRT	Jacksonville	FL	12.9	13	0.992	19.00	-		
9	BRT	Ashland Avenue BRT Phase I Project	Chicago	IL	5.4	14	0.386	116.90	-		
10	BRT	Red Line All-Electric BRT	Indianapolis	IN	13.1	28	0.468	96.33	6.17	7,400	
11	LRT	Green Line Extension	Cambridge	MA	4.7	7	0.671	2,297.62	-		
12	BRT	Laker Line BRT	Grand Rapids	MI	13.3	11	1.209	71.01	4.47	3,500	4,400
13	BRT	Michigan Avenue/Grand River Avenue BRT	Lansing	MI	8.5	27	0.315	163.92	-	-	-
14	LRT	METRO Blue Line Extension	Minneapolis	MN	13	11	1.182	1,002.00	-	-	-
15	BRT	METRO Orange Line BRT	Minneapolis	MN	17	5	3.400	150.70	-	14,000	-

16	LRT	Southwest LRT	Minneapolis	MN	14.5	16	0.906	1,774.38	20.8	17,800	31,300
17	BRT	Prospect MAX	Kansas City	MO	10	26	0.385	53.82	4.58	7,400	
18	LRT	LYNX Blue Line Extension - Northeast Corridor	Charlotte	NC	9.3	11	0.845	1,160.08	-	-	24,600
19	LRT	Durham-Orange LRT Project	Durham	NC	17.1	17	1.006	1,800.00	-	-	
20	BRT	Rapid Transit Project	Albuquerque	NM	8.8	20	0.440	126.16	2.37	16,100	-
21	BRT	4th Street/Prater Way Bus RAPID Transit	Reno	NV	3.1	8	0.388	52.57	1	6,200	7,700
22	BRT	Virginia Street BRT Extension	Reno	NV	1.8	4	0.450	60.00	-	-	-
23	BRT	River Corridor/Blue Line Bus Rapid Transit	Albany	NY	15	26	0.577	35.00	-	-	-
24	BRT	Washington/Western Bus Rapid Transit Line	Albany	NY	8	15	0.533	64.00	-	-	-
25	BRT	Cleveland Avenue BRT	Columbus	OH	15.6	32	0.488	46.82	2.66	5,700	6,600
26	LRT	Portland-Milwaukie Light Rail Project	Portland	OR	7.3	10	0.730	1,490.35	-	-	22,800
27	LRT	CBD Second Light Rail Alignment (D2)	Dallas	TX	2.4	5	0.480	650.45	3.27	19,200	
28	LRT	University Corridor LRT	Houston	TX	11.3	19	0.595	1,563.07	15.84	32,100	49,000
29	BRT	Provo-Orem Bus Rapid Transit	Provo-Orem	UT	10.5	18	0.583	149.99	3.59	11,300	-
30	BRT	Swift II BRT	Everett	WA	12.3	18	0.683	66.59	5.79	3,600	4,700
31	BRT	Montana RTS Corridor	El Paso	TX	16.8	15	1.120	46.99	4.42	4,400	-
32	LRT	Maryland National Capital Purple Line	Bethesda	MD	16.2	21	0.771	2,448.22	53.44	41,000	561,000

33	BRT	Woodhaven Boulevard Select Bus Service	New York	NY	14	-	-	231.00	-	-	-
34	LRT	Mid-Coast Corridor Transit Project	San Diego	CA	10.9	9	1.211	2,171.20	17.01	24,600	31,900
35	LRT	Lynnwood Link Extension	Seattle	WA	8.5	4	2.125	2,345.93	14.78	50,500	67,100
36	BRT	Spokane Central City Line	Spokane	WA	5.8	-	-	72.00	-	-	-
37	LRT	Tacoma Link Expansion	Tacoma	WA	2.4	6	0.400	166.00	4.8	4,100	8,600
38	BRT	Powell-Division Transit and Development	Portland	OR	14	-	-	-	-	--	-

A.4. Travel time

Travel time data used for the market values. Source: FTA (2016a); FHA (2009).

Nº	Mode	Project Name	Length (km)	City	State	Speed (km/h) Home-base work	Travel time (min)
1	BRT	Woodhaven Boulevard Select Bus Service	22.5	New York	NY	32.4	41.8
2	LRT	METRO Blue Line Extension	20.9	Minneapolis	MN	35.0	35.9
3	LRT	Southwest LRT	23.3	Minneapolis	MN	35.0	40.0
4	BRT	METRO Orange Line BRT	27.4	Minneapolis	MN	35.0	46.9
5	BRT	Ashland Avenue BRT Phase I Project	8.7	Chicago	IL	38.9	13.4
6	LRT	Tacoma Link Expansion	3.9	Tacoma	WA	40.6	5.7
7	LRT	Lynnwood Link Extension	13.7	Seattle	WA	40.6	20.2
8	LRT	Portland-Milwaukie Light Rail Project	11.7	Portland	OR	40.8	17.3
9	BRT	Powell-Division Transit and Development	22.5	Portland	OR	40.8	33.2
10	BRT	El Camino Real Corridor BRT Project	28.0	San Jose	CA	41.2	40.8
11	LRT	Third Street Light Rail Phase 2 - Central Subway	2.7	San Francisco	CA	41.2	4.0
12	BRT	Van Ness Avenue BRT	3.2	San Francisco	CA	41.2	4.7
13	LRT	Regional Connector Transit Corridor	3.1	Los Angeles	CA	41.8	4.4
14	LRT	Southeast Rail Extension	3.7	Denver	CO	43.9	5.1
15	BRT	Prospect MAX	16.1	Kansas City	MO	43.9	22.0
16	LRT	University Corridor LRT	18.2	Houston	TX	46.6	23.4
17	LRT	Mid-Coast Corridor Transit Project	17.5	San Diego	CA	46.7	22.5
18	LRT	Green Line Extension	7.6	Cambridge	MA	48.0	9.5

19	BRT	First Coast Flyer Southwest Corridor BRT	20.8	Jacksonville	FL	49.3	25.3
20	BRT	First Coast Flyer East Corridor BRT	29.8	Jacksonville	FL	49.3	36.3
21	LRT	South Central LRT Extension	8.0	Phoenix	AZ	50.3	9.6
22	LRT	LYNX Blue Line Extension - Northeast Corridor	15.0	Charlotte	NC	50.3	17.8
23	LRT	CBD Second Light Rail Alignment (D2)	3.9	Dallas	TX	50.4	4.6
24	BRT	Cleveland Avenue BRT	25.1	Columbus	OH	50.7	29.7
25	BRT	Red Line All-Electric BRT	21.1	Indianapolis	IN	50.9	24.9
26	BRT	Laker Line BRT	21.4	Grand Rapids	MI	54.2	23.7
27	LRT	Durham-Orange LRT Project	27.5	Durham	NC	55.7	29.6

A.5. Mode share

Mode share data used for the market values. Source: U. S. Census Bureau (2014).

Nº.	Metro Area	Non-private motorized mode share
1	New York-Newark-Jersey City. NY-NJ-PA	42.3%
2	San Francisco-Oakland-Hayward. CA	29.7%
3	Ithaca. NY	28.8%
4	Boulder. CO	26.3%
5	Boston-Cambridge-Newton. MA-NH	25.0%
6	Corvallis. OR	24.8%
7	Washington-Arlington-Alexandria. DC-VA-MD-WV	23.8%
8	State College. PA	23.3%
9	Glenwood Springs. CO	23.0%
10	Bremerton-Silverdale. WA	22.9%
11	Chicago-Naperville-Elgin. IL-IN-WI	20.4%
12	Seattle-Tacoma-Bellevue. WA	20.4%
13	Ames. IA	20.3%
14	Eureka-Arcata-Fortuna. CA	20.2%
15	Portland-Vancouver-Hillsboro. OR-WA	19.4%
16	Iowa City. IA	19.3%
17	Ann Arbor. MI	19.2%
18	Urban Honolulu. HI	19.1%
19	Philadelphia-Camden-Wilmington. PA-NJ-DE-MD	18.5%
20	Bridgeport-Stamford-Norwalk. CT	18.2%
21	Missoula. MT	18.2%
22	Santa Cruz-Watsonville. CA	18.1%

23	Flagstaff. AZ	17.8%
24	San Luis Obispo-Paso Robles-Arroyo Grande. CA	17.7%
25	Champaign-Urbana. IL	17.6%
26	Faribault-Northfield. MN	17.4%
27	Charlottesville. VA	17.4%
28	Trenton. NJ	17.1%
29	Bozeman. MT	17.0%
30	Eugene. OR	16.6%
31	Ukiah. CA	16.6%
32	Bend-Redmond. OR	16.5%
33	Santa Maria-Santa Barbara. CA	16.5%
34	Madison. WI	16.2%
35	Bloomington. IN	16.1%
36	Greenfield Town. MA	15.6%
37	Medford. OR	15.1%
38	Ocean City. NJ	15.1%
39	Logan. UT-ID	15.0%
40	Durham-Chapel Hill. NC	15.0%
41	Fort Collins. CO	15.0%
42	Burlington-South Burlington. VT	14.9%
43	Show Low. AZ	14.8%
44	Bellingham. WA	14.6%
45	Baltimore-Columbia-Towson. MD	14.4%
46	Key West. FL	14.4%
47	Walla Walla. WA	14.4%
48	Wooster. OH	14.4%
49	Manhattan. KS	14.2%
50	Pittsfield. MA	14.1%
51	Provo-Orem. UT	14.1%
52	Los Angeles-Long Beach-Anaheim. CA	14.0%
53	Denver-Aurora-Lakewood. CO	13.9%
54	Keene. NH	13.9%
55	Pittsburgh. PA	13.9%
56	San Diego-Carlsbad. CA	13.8%
57	Lawton. OK	13.7%
58	Rochester. MN	13.5%
59	Minneapolis-St. Paul-Bloomington. MN-WI	13.3%
60	New Haven-Milford. CT	13.3%
61	East Stroudsburg. PA	13.2%
62	Gainesville. FL	13.2%
63	Harrisonburg. VA	13.2%
64	Atlantic City-Hammonton. NJ	13.1%
65	Mankato-North Mankato. MN	13.1%
66	Lafayette-West Lafayette. IN	13.0%
67	Santa Rosa. CA	13.0%
68	Kingston. NY	12.9%
69	San Jose-Sunnyvale-Santa Clara. CA	12.9%
70	Gallup. NM	12.8%
71	Jacksonville. NC	12.8%

72	Kalispell. MT	12.7%
73	Salt Lake City. UT	12.7%
74	Truckee-Grass Valley. CA	12.7%
75	Lawrence. KS	12.6%
76	Napa. CA	12.6%
77	Austin-Round Rock. TX	12.5%
78	Oak Harbor. WA	12.5%
79	Mount Pleasant. MI	12.3%
80	Springfield. MA	12.3%
81	Morgantown. WV	12.2%
82	Sacramento--Roseville--Arden-Arcade. CA	12.2%
83	Wenatchee. WA	12.2%
84	Stevens Point. WI	12.1%
85	Blacksburg-Christiansburg-Radford. VA	11.9%
86	Athens-Clarke County. GA	11.9%
87	Claremont-Lebanon. NH-VT	11.8%
88	Santa Fe. NM	11.8%
89	Chico. CA	11.8%
90	Quincy. IL-MO	11.8%
91	Concord. NH	11.7%
92	Portland-South Portland. ME	11.7%
93	Naples-Immokalee-Marco Island. FL	11.6%
94	Ogdensburg-Massena. NY	11.6%
95	Pocatello. ID	11.6%
96	Wichita Falls. TX	11.6%
97	Prescott. AZ	11.5%
98	Albany-Schenectady-Troy. NY	11.4%
99	Duluth. MN-WI	11.4%
100	Barnstable Town. MA	11.4%
101	Kahului-Wailuku-Lahaina. HI	11.4%
102	Lancaster. PA	11.4%
103	Miami-Fort Lauderdale-West Palm Beach. FL	11.4%
104	Watertown-Fort Drum. NY	11.4%
105	Helena. MT	11.3%
106	La Crosse-Onalaska. WI-MN	11.3%
107	St. Cloud. MN	11.3%
108	Atlanta-Sandy Springs-Roswell. GA	11.2%
109	Marquette. MI	11.2%
110	Meadville. PA	11.2%
111	Spokane-Spokane Valley. WA	11.2%
112	Tucson. AZ	11.2%
113	Roseburg. OR	11.1%
114	North Port-Sarasota-Bradenton. FL	11.1%
115	Norwich-New London. CT	11.0%
116	Erie. PA	10.9%
117	Milwaukee-Waukesha-West Allis. WI	10.9%
118	New Orleans-Metairie. LA	10.9%
119	Stillwater. OK	10.9%
120	Raleigh. NC	10.9%

121	Muncie. IN	10.8%
122	Phoenix-Mesa-Scottsdale. AZ	10.8%
123	Boise City. ID	10.8%
124	Binghamton. NY	10.7%
125	Hilton Head Island-Bluffton-Beaufort. SC	10.6%
126	Fairbanks. AK	10.6%
127	Plattsburgh. NY	10.6%
128	Colorado Springs. CO	10.5%
129	Syracuse. NY	10.5%
130	Port Angeles. WA	10.4%
131	Hilo. HI	10.4%
132	Pensacola-Ferry Pass-Brent. FL	10.4%
133	Wilmington. NC	10.4%
134	Tampa-St. Petersburg-Clearwater. FL	10.3%
135	Lansing-East Lansing. MI	10.2%
136	Salem. OR	10.2%
137	South Bend-Mishawaka. IN-MI	10.2%
138	Battle Creek. MI	10.2%
139	Salinas. CA	10.1%
140	Glens Falls. NY	10.1%
141	Hartford-West Hartford-East Hartford. CT	10.0%
142	Michigan City-La Porte. IN	10.0%
143	Rome. GA	10.0%
144	Bangor. ME	9.9%
145	Las Vegas-Henderson-Paradise. NV	9.9%
146	Lexington-Fayette. KY	9.9%
147	Manchester-Nashua. NH	9.9%
148	Ogden-Clearfield. UT	9.9%
149	Providence-Warwick. RI-MA	9.9%
150	Rochester. NY	9.9%
151	Albany. OR	9.8%
152	Coeur d'Alene. ID	9.8%
153	Branson. MO	9.7%
154	Idaho Falls. ID	9.7%
155	Indiana. PA	9.7%
156	Mount Vernon-Anacortes. WA	9.7%
157	Cleveland-Elyria. OH	9.6%
158	Corning. NY	9.6%
159	Anchorage. AK	9.5%
160	Cape Girardeau. MO-IL	9.5%
161	Eau Claire. WI	9.5%
162	Traverse City. MI	9.5%
163	Waterloo-Cedar Falls. IA	9.5%
164	Auburn. NY	9.4%
165	Fond du Lac. WI	9.4%
166	Morehead City. NC	9.4%
167	Asheville. NC	9.3%
168	Augusta-Waterville. ME	9.3%
169	Charleston-North Charleston. SC	9.3%

170	Russellville. AR	9.3%
171	Torrington. CT	9.3%
172	Worcester. MA-CT	9.3%
173	Palm Bay-Melbourne-Titusville. FL	9.2%
174	Tallahassee. FL	9.2%
175	Charleston-Mattoon. IL	9.1%
176	Columbia. MO	9.1%
177	Klamath Falls. OR	9.1%
178	Savannah. GA	9.1%
179	Harrisburg-Carlisle. PA	9.0%
180	Kapaa. HI	9.0%
181	Lebanon. PA	9.0%
182	Olympia-Tumwater. WA	9.0%
183	Reading. PA	9.0%
184	Albuquerque. NM	8.9%
185	Allentown-Bethlehem-Easton. PA-NJ	8.9%
186	Billings. MT	8.9%
187	Columbus. OH	8.9%
188	Grand Junction. CO	8.9%
189	Olean. NY	8.9%
190	Reno. NV	8.9%
191	Elmira. NY	8.8%
192	Grand Forks. ND-MN	8.8%
193	Greeley. CO	8.8%
194	Lincoln. NE	8.8%
195	St. Louis. MO-IL	8.8%
196	Sebring. FL	8.8%
197	Buffalo-Cheektowaga-Niagara Falls. NY	8.7%
198	Marion. IN	8.7%
199	Cape Coral-Fort Myers. FL	8.7%
200	Dubuque. IA	8.7%
201	Kankakee. IL	8.7%
202	Orlando-Kissimmee-Sanford. FL	8.7%
203	Oxnard-Thousand Oaks-Ventura. CA	8.7%
204	Redding. CA	8.7%
205	Wausau. WI	8.7%
206	Richmond. VA	8.6%
207	Bloomington. IL	8.6%
208	Bowling Green. KY	8.6%
209	Charlotte-Concord-Gastonia. NC-SC	8.6%
210	Deltona-Daytona Beach-Ormond Beach. FL	8.6%
211	Fresno. CA	8.6%
212	Grand Island. NE	8.6%
213	Merced. CA	8.6%
214	Sherman-Denison. TX	8.6%
215	Whitewater-Elkhorn. WI	8.5%
216	Williamsport. PA	8.5%
217	Salisbury. MD-DE	8.5%
218	Virginia Beach-Norfolk-Newport News. VA-NC	8.5%

219	Cincinnati. OH-KY-IN	8.4%
220	Columbia. SC	8.4%
221	Niles-Benton Harbor. MI	8.4%
222	Parkersburg-Vienna. WV	8.4%
223	Riverside-San Bernardino-Ontario. CA	8.4%
224	St. George. UT	8.4%
225	Sheboygan. WI	8.3%
226	Winchester. VA-WV	8.3%
227	Great Falls. MT	8.3%
228	Kalamazoo-Portage. MI	8.3%
229	Gettysburg. PA	8.2%
230	San Antonio-New Braunfels. TX	8.2%
231	Yakima. WA	8.2%
232	Daphne-Fairhope-Foley. AL	8.2%
233	Stockton-Lodi. CA	8.2%
234	Vallejo-Fairfield. CA	8.2%
235	Columbus. GA-AL	8.1%
236	Panama City. FL	8.1%
237	Racine. WI	8.1%
238	Utica-Rome. NY	8.1%
239	Yuba City. CA	8.1%
240	Dallas-Fort Worth-Arlington. TX	8.1%
241	San Juan-Carolina-Caguas. PR	8.1%
242	Twin Falls. ID	8.0%
243	Cleveland. TN	8.0%
244	College Station-Bryan. TX	8.0%
245	Fargo. ND-MN	8.0%
246	Lynchburg. VA	8.0%
247	Dayton. OH	7.9%
248	Ocala. FL	7.9%
249	Sierra Vista-Douglas. AZ	7.9%
250	Adrian. MI	7.8%
251	Brainerd. MN	7.8%
252	Springfield. IL	7.8%
253	Charleston. WV	7.8%
254	Chattanooga. TN-GA	7.8%
255	Longview. WA	7.8%
256	Louisville/Jefferson County. KY-IN	7.8%
257	Davenport-Moline-Rock Island. IA-IL	7.7%
258	Grand Rapids-Wyoming. MI	7.7%
259	Lewiston-Auburn. ME	7.7%
260	Pueblo. CO	7.7%
261	Richmond-Berea. KY	7.7%
262	Saginaw. MI	7.7%
263	Somerset. PA	7.7%
264	Alamogordo. NM	7.6%
265	San Angelo. TX	7.6%
266	Wheeling. WV-OH	7.6%
267	Centralia. WA	7.6%

268	Kansas City. MO-KS	7.6%
269	Sioux Falls. SD	7.5%
270	Sunbury. PA	7.5%
271	Houston-The Woodlands-Sugar Land. TX	7.5%
272	Jacksonville. FL	7.5%
273	Warsaw. IN	7.5%
274	Weirton-Steubenville. WV-OH	7.5%
275	Wisconsin Rapids-Marshfield. WI	7.5%
276	Danville. IL	7.4%
277	Elkhart-Goshen. IN	7.4%
278	Nashville-Davidson--Murfreesboro--Franklin. TN	7.4%
279	Crestview-Fort Walton Beach-Destin. FL	7.3%
280	El Paso. TX	7.3%
281	Richmond. IN	7.3%
282	Kennewick-Richland. WA	7.3%
283	Watertown-Fort Atkinson. WI	7.3%
284	Canton-Massillon. OH	7.2%
285	Dover. DE	7.2%
286	Scranton--Wilkes-Barre--Hazleton. PA	7.2%
287	Appleton. WI	7.1%
288	Bismarck. ND	7.1%
289	Port St. Lucie. FL	7.1%
290	Portsmouth. OH	7.1%
291	Sioux City. IA-NE-SD	7.1%
292	Springfield. MO	7.1%
293	Toledo. OH	7.1%
294	Auburn-Opelika. AL	7.1%
295	Green Bay. WI	7.0%
296	Greenville. NC	7.0%
297	Indianapolis-Carmel-Anderson. IN	7.0%
298	Killeen-Temple. TX	7.0%
299	Moses Lake. WA	7.0%
300	Springfield. OH	7.0%
301	Bloomsburg-Berwick. PA	6.9%
302	El Centro. CA	6.9%
303	McAllen-Edinburg-Mission. TX	6.9%
304	Minot. ND	6.9%
305	Owosso. MI	6.9%
306	Peoria. IL	6.9%
307	Rapid City. SD	6.9%
308	Akron. OH	6.8%
309	Ashtabula. OH	6.8%
310	Des Moines-West Des Moines. IA	6.8%
311	Fayetteville. NC	6.8%
312	Hagerstown-Martinsburg. MD-WV	6.8%
313	Lakeland-Winter Haven. FL	6.8%
314	Modesto. CA	6.8%
315	Winston-Salem. NC	6.8%
316	Carbondale-Marion. IL	6.7%

317	Cheyenne. WY	6.7%
318	Greensboro-High Point. NC	6.7%
319	Oshkosh-Neenah. WI	6.7%
320	Albany. GA	6.6%
321	Joplin. MO	6.6%
322	Las Cruces. NM	6.6%
323	Marinette. WI-MI	6.6%
324	Searcy. AR	6.6%
325	Alexandria. LA	6.5%
326	Roanoke. VA	6.5%
327	Cedar Rapids. IA	6.4%
328	Detroit-Warren-Dearborn. MI	6.4%
329	Fayetteville-Springdale-Rogers. AR-MO	6.4%
330	Jamestown-Dunkirk-Fredonia. NY	6.4%
331	Johnstown. PA	6.4%
332	Manitowoc. WI	6.4%
333	Omaha-Council Bluffs. NE-IA	6.4%
334	Huntington-Ashland. WV-KY-OH	6.3%
335	Janesville-Beloit. WI	6.3%
336	New Castle. PA	6.3%
337	Waco. TX	6.3%
338	Decatur. IL	6.2%
339	Farmington. NM	6.2%
340	Fort Wayne. IN	6.2%
341	Lubbock. TX	6.2%
342	Youngstown-Warren-Boardman. OH-PA	6.2%
343	Corpus Christi. TX	6.1%
344	Madera. CA	6.1%
345	Wichita. KS	6.1%
346	York-Hanover. PA	6.1%
347	Flint. MI	6.0%
348	Marion. OH	6.0%
349	Lafayette. LA	6.0%
350	Myrtle Beach-Conway-North Myrtle Beach. SC-NC	6.0%
351	Ottawa-Peru. IL	6.0%
352	Danville. VA	5.9%
353	Augusta-Richmond County. GA-SC	5.9%
354	Chambersburg-Waynesboro. PA	5.9%
355	Greenville-Anderson-Mauldin. SC	5.9%
356	Mobile. AL	5.9%
357	Pine Bluff. AR	5.9%
358	Oklahoma City. OK	5.8%
359	Tulsa. OK	5.8%
360	Visalia-Porterville. CA	5.8%
361	California-Lexington Park. MD	5.8%
362	Elizabethtown-Fort Knox. KY	5.8%
363	Monroe. MI	5.8%
364	Pottsville. PA	5.8%
365	Yuma. AZ	5.8%

366	Baton Rouge. LA	5.7%
367	Gulfport-Biloxi-Pascagoula. MS	5.7%
368	Jackson. MI	5.7%
369	Clarksville. TN-KY	5.6%
370	Rocky Mount. NC	5.6%
371	Tuscaloosa. AL	5.6%
372	Elizabeth City. NC	5.5%
373	Gainesville. GA	5.5%
374	Hanford-Corcoran. CA	5.5%
375	Shelby. NC	5.5%
376	Terre Haute. IN	5.5%
377	DuBois. PA	5.4%
378	Hammond. LA	5.4%
379	Johnson City. TN	5.4%
380	Bakersfield. CA	5.4%
381	Florence. SC	5.4%
382	Knoxville. TN	5.4%
383	Mansfield. OH	5.4%
384	Memphis. TN-MS-AR	5.4%
385	St. Joseph. MO-KS	5.4%
386	Shawnee. OK	5.4%
387	Evansville. IN-KY	5.3%
388	Gadsden. AL	5.3%
389	Hot Springs. AR	5.3%
390	Ponce. PR	5.3%
391	Salem. OH	5.3%
392	Victoria. TX	5.3%
393	Beaver Dam. WI	5.3%
394	Topeka. KS	5.3%
395	Casper. WY	5.2%
396	Macon. GA	5.2%
397	New Bern. NC	5.2%
398	Vineland-Bridgeton. NJ	5.2%
399	Talladega-Sylacauga. AL	5.1%
400	Holland. MI	5.1%
401	Abilene. TX	5.0%
402	Florence-Muscle Shoals. AL	5.0%
403	Midland. MI	5.0%
404	Muskogee. OK	5.0%
405	Texarkana. TX-AR	5.0%
406	Tullahoma-Manchester. TN	5.0%
407	Beckley. WV	4.9%
408	Birmingham-Hoover. AL	4.9%
409	Little Rock-North Little Rock-Conway. AR	4.9%
410	Rockford. IL	4.9%
411	Aguadilla-Isabela. PR	4.8%
412	Altoona. PA	4.8%
413	Hattiesburg. MS	4.8%
414	Muskegon. MI	4.8%

415	Bluefield. WV-VA	4.7%
416	Burlington. NC	4.7%
417	Greenwood. SC	4.7%
418	Kokomo. IN	4.7%
419	Lake Charles. LA	4.7%
420	Morristown. TN	4.7%
421	Shreveport-Bossier City. LA	4.7%
422	Columbus. IN	4.6%
423	Laredo. TX	4.6%
424	Longview. TX	4.5%
425	Amarillo. TX	4.5%
426	Goldsboro. NC	4.5%
427	Meridian. MS	4.5%
428	Cookeville. TN	4.4%
429	Houma-Thibodaux. LA	4.4%
430	Jonesboro. AR	4.4%
431	Montgomery. AL	4.3%
432	Fort Smith. AR-OK	4.2%
433	Monroe. LA	4.2%
434	Albertville. AL	4.2%
435	New Philadelphia-Dover. OH	4.2%
436	Valdosta. GA	4.2%
437	Brownsville-Harlingen. TX	3.9%
438	Bay City. MI	3.8%
439	Zanesville. OH	3.8%
440	Dothan. AL	3.8%
441	Huntsville. AL	3.7%
442	Jefferson City. MO	3.7%
443	Kingsport-Bristol-Bristol. TN-VA	3.7%
444	Lake Havasu City-Kingman. AZ	3.7%
445	Spartanburg. SC	3.7%
446	Tyler. TX	3.7%
447	Jackson. MS	3.6%
448	Hickory-Lenoir-Morganton. NC	3.6%
449	Jackson. TN	3.5%
450	Mount Airy. NC	3.5%
451	Lima. OH	3.4%
452	Anniston-Oxford-Jacksonville. AL	3.2%
453	Odessa. TX	3.0%
454	Warner Robins. GA	2.9%
455	Beaumont-Port Arthur. TX	2.7%
456	Dalton. GA	2.6%
457	Dunn. NC	2.5%
458	Midland. TX	1.9%
459	Lumberton. NC	1.7%

A.6. Real Estate

Real estate data used for the market values. Source: FTA (2016a); Zillow (2016).

Nº	City	State	Median home value (US$/$m^2$)
1	San Francisco	CA	9,741
2	Cambridge	MA	6,717
3	San Jose	CA	5,619
4	Bethesda	MD	4,704
5	New York	NY	4,542
6	Los Angeles	CA	4,144
7	Seattle	WA	4,080
8	San Diego	CA	3,886
9	Portland	OR	3,014
10	Denver	CO	2,917
11	Everett	WA	2,002
12	Minneapolis	MN	1,991
13	Reno	NV	1,808
14	Chicago	IL	1,701
15	Tacoma	WA	1,625
16	Provo-Orem	UT	1,588
17	Phoenix	AZ	1,345
18	Spokane	WA	1,313
19	Albany	NY	1,206
20	Albuquerque	NM	1,141
21	Durham	NC	1,098
22	Dallas	TX	1,066
23	Charlotte	NC	1,023
24	Houston	TX	958
25	Grand Rapids	MI	904
26	Jacksonville	FL	904
27	Kansas City	MO	872
28	Columbus	OH	861
29	El Paso	TX	818
30	Indianapolis	IN	753
31	Lansing	MI	635

A.7. E-mail example

An example of the e-mail sent to the experts.

Gmail

Request for Expert Opinion

Marcos Paulo <pdst12004@fe.up.pt>
Rascunho

Dear XXX,

I'm Marcos Schlickmann, a PhD candidate from the MIT Portugal Program in Transportation Systems.

I'm researching about the incorporation of land use impacts on BRT and LRT decision making. I would like to kindly ask you to answer the following survey, it won't take more than 30 minutes:

Survey (Available until 04/30/2016. After answering you may be contacted again to revise some answers)

If you would like to know more about my research please find attached.

If you have any doubt or want more information on my research, please don't hesitate to contact me.

Thank you very much,

Marcos Paulo Schlickmann
PhD Candidate in Transportation Systems
MIT Portugal Program

A.8. List of experts

The list of experts who answered the survey.

Nº.	Country	Name	Category	Current Institutions
1	Portugal	Álvaro Seco	Academia	Metro Mondego
2	Portugal	André Remédio	Consultancy	ENGIMIND
3	USA	Anson Stewart	Academia	MIT
4	Brazil	Anthony Ling	Consultancy	Instituto Ling
5	Portugal	António Couto	Academia	FEUP
6	Portugal	António Lobo	Academia	FEUP
7	Brazil	Antônio Nelson	Academia	USP
8	The Netherlands	Bert van Wee	Academia	TU Delft
9	USA	David Levinson	Academia	UMinnesota
10	Portugal	Jorge Freire de Sousa	Academia	FEUP, STCP
11	Brazil	Lino Marujo	Academia	COPPE-UFRJ
12	USA	Rui Neiva	Consultancy	Eno
13	Germany	Sebastian Ebert	Academia	FEUP
14	Portugal	Tiago Farias	Public Sector	IST and Transportes de Lisboa
15	Canada	Todd Litman	Consultancy	VTPI
16	Brazil	Victor Carvalho Pinto	Public Sector	Senado Federal
17	Brazil	Wagner Colombini Martins	Consultancy	Logit

A.9. Survey responses

The survey responses were treated in a “standard” worksheet (Goepel, 2013).

The answers for the main criteria – Finance, Transport and Land Use – are depicted below.

Consolidated answers:

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **07.06.2015** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	3	Number of criteria (2 to 10)	Scale:	1	Linear
N=	17	Number of Participants (1 to 20)	α:	0,1	Consensus: **82,8%**
p=	0	selected Participant (0=consol.)	2	7	**Consolidated**

Objective Main Criteria

Author MPS

Date 18-Mar-16 Thresh: 1E-07 Iterations: 8 EVM check: 2,2E-08

Table

	Criterion	**Comment**	**Weights**	**Rk**
1	Finance		27,3%	2
2	Transport		52,4%	1
3	Land use		20,2%	3

Result

Eigenvalue lambda: **3,000**

Consistency Ratio 0,37 GCI: 0,00 CR: 0,0%

Matrix

		Finance 1	Transport 2	Land use 3	0 4	0 5	0 6	0 7	0 8	0 9	0 10
Finance	1	-	1/2	1 1/3	-	-	-	-	-	-	-
Transport	2	2	-	2 3/5	-	-	-	-	-	-	-
Land use	3	3/4	3/8	-	-	-	-	-	-	-	-

normalized principal Eigenvector

27,34%
52,42%
20,24%

Individual answers:

AHP Analytic Hierarchy Process

n= 3 Input 1

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		11%
2	Transport		48%
3	Land use		41%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Anson Stewart (A)	1	18/03/2016	0,1	3%	1

i	j	Criteria A	B	more important ? A or B	Scale (1-9)
1	2	Finance	Transport	B	5
1	3		Land use	B	3
2	3	Transport	Land use	A	1

A
B

AHP Analytic Hierarchy Process

n= 3 Input 2

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		14%
2	Transport		57%
3	Land use		29%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Antonio Nelson (A)	1	18/03/2016	0,1	0%	1

i	j	Criteria A	B	more important ? A or B	Scale (1-9)
1	2	Finance	Transport	B	4
1	3		Land use	B	2
2	3	Transport	Land use	A	2

A
B

AHP Analytic Hierarchy Process

n= 3 Input 3

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		10%
2	Transport		70%
3	Land use		20%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Sebastian Ebert (A)	1	18/03/2016	0,1	14%	1

i	j	Criteria A	B	more important ? A or B	Scale (1-9)		
1	2	Finance	Transport	B	5	3	B7
1	3		Land use	B	3	2	B2
2	3	Transport	Land use	A	5	1	A3

A
B

AHP Analytic Hierarchy Process

n= 3 Input 4

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		28%
2	Transport		58%
3	Land use		14%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
António Lobo (A)	1	18/03/2016	0,1	14%	1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)		
1	2	Finance	Transport	B	3	2	B2
1	3		Land use	A	3	3	A2
2	3	Transport	Land use	A	3	1	A4

A

B

AHP Analytic Hierarchy Process

n= 3 Input 5

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		26%
2	Transport		64%
3	Land use		10%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Jorge Freire Sousa (A)	1	22/04/2016	0,1	4%	1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Finance	Transport	B	3
1	3		Land use	A	3
2	3	Transport	Land use	A	5

A

B

AHP Analytic Hierarchy Process

n= 3 Input 6

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		40%
2	Transport		40%
3	Land use		20%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Lino Marujo (A)	1	22/04/2016	0,1	0%	1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Finance	Transport	A	1
1	3		Land use	A	2
2	3	Transport	Land use	A	2

A

B

AHP Analytic Hierarchy Process

n= 3 Input 7

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		9%
2	Transport		45%
3	Land use		45%

Name	Weight	Date
Todd Litman (C)	1	22/04/2016

α: 0,1 CR: 0% (Consistency Ratio) Scale: 1

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Finance	Transport	B	5
1	3		Land use	B	5
2	3	Transport	Land use	A	1

A
B

AHP Analytic Hierarchy Process

n= 3 Input 8

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		43%
2	Transport		43%
3	Land use		14%

Name	Weight	Date
Bert van Wee (A)	1	22/04/2016

α: 0,1 CR: 0% (Consistency Ratio) Scale: 1

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Finance	Transport	A	1
1	3		Land use	A	3
2	3	Transport	Land use	A	3

A
B

AHP Analytic Hierarchy Process

n= 3 Input 9

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		46%
2	Transport		46%
3	Land use		8%

Name	Weight	Date
Anthony Ling (C)	1	22/04/2016

α: 0,1 CR: 0% (Consistency Ratio) Scale: 1

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Finance	Transport	A	1
1	3		Land use	A	6
2	3	Transport	Land use	A	6

A
B

AHP Analytic Hierarchy Process

n= 3 Input 10

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		42%
2	Transport		48%
3	Land use		9%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Rui Neiva (C)	1	22/04/2016	0,1	2%	1

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Finance	Transport	A	1
1	3		Land use	A	4
2	3	Transport	Land use	A	6

A
B

AHP Analytic Hierarchy Process

n= 3 Input 11

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		38%
2	Transport		11%
3	Land use		51%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Victor Pinto (P)	1	22/04/2016	0,1	17%	1

i	j	A	B	more important ? A or B	Scale (1-9)		
1	2	Finance	Transport	A	5	3	A3
1	3		Land use	B	2	1	B1
2	3	Transport	Land use	B	3	1	B4

A
B

AHP Analytic Hierarchy Process

n= 3 Input 12

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		16%
2	Transport		59%
3	Land use		25%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Tiago Farias (P)	1	19/07/2016	0,1	6%	1

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Finance	Transport	B	3
1	3		Land use	B	2
2	3	Transport	Land use	A	3

A
B

AHP Analytic Hierarchy Process

n= 3 | Input 13

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		26%
2	Transport		64%
3	Land use		10%

Name	Weight	Date
Wagner C Martins (C)	1	19/07/2016

α: 0,1 CR: 4% (Consistency Ratio) | Scale: 1

i	j	A	B	A or B	Scale (1-9)
1	2	Finance	Transport	B	3
1	3		Land use	A	3
2	3	Transport	Land use	A	5

AHP Analytic Hierarchy Process

n= 3 | Input 14

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		22%
2	Transport		63%
3	Land use		15%

Name	Weight	Date
André Remédio (C)	1	19/07/2016

α: 0,1 CR: 11% (Consistency Ratio) | Scale: 1

i	j	A	B	A or B	Scale (1-9)		
1	2	Finance	Transport	B	4	1	B3
1	3		Land use	A	2	3	A1
2	3	Transport	Land use	A	3	1	A4

AHP Analytic Hierarchy Process

n= 3 Input 15

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		73%
2	Transport		19%
3	Land use		8%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
David Levinson (A)	1	19/07/2016	0,1	7%	1

i	j	Criteria A	B	more important ? A or B	Scale (1-9)
1	2	Finance	Transport	A	5
1	3		Land use	A	7
2	3	Transport	Land use	A	3

A
B

AHP Analytic Hierarchy Process

n= 3 Input 16

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		16%
2	Transport		54%
3	Land use		30%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
António Couto (A)	1	19/07/2016	0,1	1%	1

i	j	Criteria A	B	more important ? A or B	Scale (1-9)
1	2	Finance	Transport	B	3
1	3		Land use	B	2
2	3	Transport	Land use	A	2

A
B

AHP Analytic Hierarchy Process

n= 3 Input 17

Objective: Main Criteria

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Finance		24%
2	Transport		63%
3	Land use		14%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Álvaro Seco (A)	1	19/07/2016	0,1	2%	1

i	j	Criteria A	B	more important ? A or B	Scale (1-9)
1	2	Finance	Transport	B	3
1	3		Land use	A	2
2	3	Transport	Land use	A	4

A
B

The answers for the subcriteria – Capital Costs, Operating Costs and Revenues – are depicted below.

Consolidated answers:

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **07.06.2015** | Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	3	Number of criteria (2 to 10)	Scale:	1	Linear
N=	17	Number of Participants (1 to 20)	α:	0,1	Consensus: 78,0%
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective Finance

Author MPS

Date 18-Mar-16 Thresh: 1E-07 Iterations: 8 EVM check: 2,3E-08

Table	**Criterion**	**Comment**	**Weights**	**Rk**
1	Capital Costs		21,7%	3
2	O&M		33,0%	2
3	Revenues		45,3%	1

Result

Eigenvalue lambda: 3,005

Consistency Ratio 0,37 GCI: 0,02 CR: 0,5%

Matrix

		Capital Costs 1	O&M 2	Revenues 3	0 4	0 5	0 6	0 7	0 8	0 9	0 10	normalized principal Eigenvector
Capital Costs	1	-	3/5	1/2	-	-	-	-	-	-	-	21,70%
O&M	2	1 5/8	-	2/3	-	-	-	-	-	-	-	33,02%
Revenues	3	2	1 1/2	-	-	-	-	-	-	-	-	45,28%

Individual answers:

AHP Analytic Hierarchy Process

n= 3 | Input 1

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		12%
2	O&M		53%
3	Revenues		35%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Anson Stewart (A)	1	18/03/2016	0,1	18%	1

i	j	A	B	more important ? A or B	Scale (1-9)		
1	2	Capital Costs	O&M	B	7	3	B5
1	3		Revenues	B	2	1	B3
2	3	O&M	Revenues	B	1	2	A2

A B

AHP Analytic Hierarchy Process

n= 3 | Input 2

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		22%
2	O&M		46%
3	Revenues		32%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Antonio Nelson (A)	1	18/03/2016	0,1	14%	1

i	j	A	B	more important ? A or B	Scale (1-9)		
1	2	Capital Costs	O&M	B	3	1	B2
1	3		Revenues	A	1	3	B1
2	3	O&M	Revenues	B	1	1	A1

A B

AHP Analytic Hierarchy Process

n= 3 | Input 3

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		22%
2	O&M		46%
3	Revenues		32%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Sebastian Ebert (A)	1	18/03/2016	0,1	14%	1

i	j	A	B	more important ? A or B	Scale (1-9)		
1	2	Capital Costs	O&M	B	3	1	B2
1	3		Revenues	A	1	3	B1
2	3	O&M	Revenues	A	1	1	A1

A B

AHP Analytic Hierarchy Process

n= 3 Input 4

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		9%
2	O&M		54%
3	Revenues		37%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
António Lobo (A)	1	18/03/2016	0,1	14%	1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)		
1	2	Capital Costs	O&M	B	9	3	B6
1	3		Revenues	B	3	2	B4
2	3	O&M	Revenues	A	1	1	A1

A

B

AHP Analytic Hierarchy Process

n= 3 Input 5

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		33%
2	O&M		33%
3	Revenues		33%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Jorge Freire Sousa (A)	1	22/04/2016	0,1	0%	1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Capital Costs	O&M	A	1
1	3		Revenues	A	1
2	3	O&M	Revenues	A	1

A

B

AHP Analytic Hierarchy Process

n= 3 Input 6

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		17%
2	O&M		17%
3	Revenues		67%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Lino Marujo (A)	1	22/04/2016	0,1	0%	1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Capital Costs	O&M	A	1
1	3		Revenues	B	4
2	3	O&M	Revenues	B	4

A

B

AHP Analytic Hierarchy Process

n= 3 Input 7

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		10%
2	O&M		26%
3	Revenues		64%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Todd Litman (A)	1	22/04/2016	0,1	4%	1

i	j	A	B	A or B	Scale (1-9)
1	2	Capital Costs	O&M	B	3
1	3		Revenues	B	5
2	3	O&M	Revenues	B	3

A
B

AHP Analytic Hierarchy Process

n= 3 Input 8

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		21%
2	O&M		55%
3	Revenues		24%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Bert van Wee (A)	1	22/04/2016	0,1	2%	1

i	j	A	B	A or B	Scale (1-9)
1	2	Capital Costs	O&M	B	3
1	3		Revenues	A	1
2	3	O&M	Revenues	A	2

A
B

AHP Analytic Hierarchy Process

n= 3 Input 9

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		10%
2	O&M		10%
3	Revenues		80%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Anthony Ling (C)	1	22/04/2016	0,1	0%	1

i	j	A	B	A or B	Scale (1-9)
1	2	Capital Costs	O&M	A	1
1	3		Revenues	B	8
2	3	O&M	Revenues	B	8

A
B

AHP Analytic Hierarchy Process

n= 3 Input 10

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		11%
2	O&M		48%
3	Revenues		41%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Rui Neiva (C)	1	22/04/2016	0,1	3%	1

i	j	Criteria A	B	more important ? A or B	Scale (1-9)
1	2	Capital Costs	O&M	B	5
1	3		Revenues	B	3
2	3	O&M	Revenues	A	1

A
B

AHP Analytic Hierarchy Process

n= 3 Input 11

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		9%
2	O&M		62%
3	Revenues		30%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Victor Pinto (P)	1	22/04/2016	0,1	14%	1

i	j	Criteria A	B	more important ? A or B	Scale (1-9)		
1	2	Capital Costs	O&M	B	5	1	B7
1	3		Revenues	B	5	1	B3
2	3	O&M	Revenues	A	3	3	A2

A
B

AHP Analytic Hierarchy Process

n= 3 Input 12

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		46%
2	O&M		22%
3	Revenues		32%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Tiago Farias (P)	1	19/07/2016	0,1	14%	1

i	j	Criteria A	B	more important ? A or B	Scale (1-9)		
1	2	Capital Costs	O&M	A	3	2	A2
1	3		Revenues	A	1	1	A1
2	3	O&M	Revenues	A	1	2	B1

A
B

AHP Analytic Hierarchy Process

n= 3 Input 13

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		14%
2	O&M		14%
3	Revenues		71%

Name	Weight	Date	α:	CR:	Scale
Wagner C Martins (C)	1	19/07/2016	0,1	0%	1

Consistency Ratio

i	j	A	B	A or B	Scale (1-9)
1	2	Capital Costs	O&M	A	1
1	3		Revenues	B	5
2	3	O&M	Revenues	B	5

Scale: A B

AHP Analytic Hierarchy Process

n= 3 Input 14

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		9%
2	O&M		30%
3	Revenues		62%

Name	Weight	Date	α:	CR:	Scale
André Remédio (C)	1	19/07/2016	0,1	14%	1

Consistency Ratio

i	j	A	B	A or B	Scale (1-9)		
1	2	Capital Costs	O&M	B	5	3	B3
1	3		Revenues	B	5	1	B7
2	3	O&M	Revenues	B	3	2	B2

Scale: A B

AHP Analytic Hierarchy Process

n= 3 Input 15

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		66%
2	O&M		20%
3	Revenues		15%

Name	Weight	Date	α:	CR:	Scale
David Levinson (A)	1	19/07/2016	0,1	17%	1

Consistency Ratio

i	j	A	B	A or B	Scale (1-9)		
1	2	Capital Costs	O&M	A	5	3	A3
1	3		Revenues	A	3	1	A4
2	3	O&M	Revenues	A	2	2	A1

Scale: A B

AHP Analytic Hierarchy Process

n= 3 Input 16

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		31%
2	O&M		20%
3	Revenues		49%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Antonio Couto (A)	1	19/07/2016	0,1	6%	1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Capital Costs	O&M	A	2
1	3		Revenues	B	2
2	3	O&M	Revenues	B	2

AHP Analytic Hierarchy Process

n= 3 Input 17

Objective: Finance

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Capital Costs		64%
2	O&M		10%
3	Revenues		26%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Álvaro Seco (A)	1	19/07/2016	0,1	4%	1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Capital Costs	O&M	A	5
1	3		Revenues	A	3
2	3	O&M	Revenues	B	3

The answers for the subcriteria – Travel Time, Mode Share, Transfers and Emissions – are depicted below.

Consolidated answers:

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 07.06.2015 | Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	4	Number of criteria (2 to 10)	Scale:	1	Linear
N=	17	Number of Participants (1 to 20)	α:	0,1	Consensus: 68,9%
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective Transport

Author MPS

Date 18-Mar-16 | Thresh: 1E-07 | Iterations: 6 | EVM check: 2,4E-08

Table

Criterion	Comment	Weights	Rk
1 Travel time		42,7%	1
2 Mode Share		23,5%	2
3 Transfers		17,0%	3
4 Emissions		16,8%	4

Result

Eigenvalue		lambda:	4,029
Consistency Ratio	0,37 GCI: 0,04	CR:	1,1%

Matrix

		Travel time 1	Mode Share 2	Transfers 3	Emissions 4	0 5	0 6	0 7	0 8	0 9	0 10	normalized principal Eigenvector
Travel time	1	-	2	2 1/3	2 1/2	-	-	-	-	-	-	42,74%
Mode Share	2	1/2	-	1 1/4	1 3/4	-	-	-	-	-	-	23,49%
Transfers	3	3/7	4/5	-	5/6	-	-	-	-	-	-	16,98%
Emissions	4	2/5	4/7	1 1/5	-	-	-	-	-	-	-	16,79%

Individual answers:

AHP Analytic Hierarchy Process

n= 4 Input 1

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		15%
2	Mode Share		37%
3	Transfers		20%
4	Emissions		28%

Name	Weight	Date
Anson Stewart (A)	1	18/03/2016

α: 0,1 CR: 3% Consistency Ratio 1 Scale

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Travel time	Mode Share	B	3
1	3		Transfers	A	1
1	4		Emissions	B	2
2	3	Mode Share	Transfers	A	2
2	4		Emissions	A	1
3	4	Transfers	Emissions	A	1

A
B

AHP Analytic Hierarchy Process

n= 4 Input 2

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		58%
2	Mode Share		7%
3	Transfers		12%
4	Emissions		23%

Name	Weight	Date
Antonio Nelson (A)	1	18/03/2016

α: 0,1 CR: 1% Consistency Ratio 1 Scale

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Travel time	Mode Share	A	7
1	3		Transfers	A	5
1	4		Emissions	A	3
2	3	Mode Share	Transfers	B	2
2	4		Emissions	B	4
3	4	Transfers	Emissions	B	2

A
B

AHP Analytic Hierarchy Process

n= 4 Input 3

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		63%
2	Mode Share		13%
3	Transfers		13%
4	Emissions		13%

Name	Weight	Date	α:	CR:	Scale
Sebastian Ebert (A)	1	18/03/2016	0,1	0%	1

Consistency Ratio

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Travel time	Mode Share	A	5
1	3		Transfers	A	5
1	4		Emissions	A	5
2	3	Mode Share	Transfers	A	1
2	4		Emissions	A	1
3	4	Transfers	Emissions	A	1

A

B

AHP Analytic Hierarchy Process

n= 4 Input 4

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		38%
2	Mode Share		10%
3	Transfers		9%
4	Emissions		43%

Name	Weight	Date	α:	CR:	Scale
António Lobo (A)	1	18/03/2016	0,1	1%	1

Consistency Ratio

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Travel time	Mode Share	A	3
1	3		Transfers	A	5
1	4		Emissions	A	1
2	3	Mode Share	Transfers	A	1
2	4		Emissions	B	5
3	4	Transfers	Emissions	B	5

A

B

AHP Analytic Hierarchy Process

n= 4 Input 5

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		39%
2	Mode Share		39%
3	Transfers		8%
4	Emissions		14%

Name	Weight	Date		
Jorge Freire Sousa (A)	1	22/04/2016		

α: 0,1 CR: 0% Consistency Ratio 1 Scale

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Travel time	Mode Share	A	1
1	3		Transfers	A	5
1	4		Emissions	A	3
2	3	Mode Share	Transfers	A	5
2	4		Emissions	A	3
3	4	Transfers	Emissions	B	2

A
B

AHP Analytic Hierarchy Process

n= 4 Input 6

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		18%
2	Mode Share		38%
3	Transfers		20%
4	Emissions		24%

Name	Weight	Date
Lino Marujo (A)	1	22/04/2016

α: 0,1 CR: 19% Consistency Ratio 1 Scale

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)		
1	2	Travel time	Mode Share	A	1	2	B2
1	3		Transfers	B	3	1	B1
1	4		Emissions	A	1		
2	3	Mode Share	Transfers	A	3		
2	4		Emissions	A	2		
3	4	Transfers	Emissions	B	2	3	B1

A
B

AHP Analytic Hierarchy Process

n= 4 Input 7

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		20%
2	Mode Share		57%
3	Transfers		10%
4	Emissions		13%

Name	Weight	Date	α:	Consistency Ratio	Scale
Todd Litman (A)	1	22/04/2016	0,1	CR: 3%	1

i	j	Criteria A	B	more important ? A or B	Scale (1-9)
1	2	Travel time	Mode Share	B	3
1	3		Transfers	A	3
1	4		Emissions	A	1
2	3	Mode Share	Transfers	A	5
2	4		Emissions	A	5
3	4	Transfers	Emissions	A	1

A
B

AHP Analytic Hierarchy Process

n= 4 Input 8

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		28%
2	Mode Share		55%
3	Transfers		9%
4	Emissions		8%

Name	Weight	Date	α:	Consistency Ratio	Scale
Bert van Wee (A)	1	22/04/2016	0,1	CR: 5%	1

i	j	Criteria A	B	more important ? A or B	Scale (1-9)
1	2	Travel time	Mode Share	B	3
1	3		Transfers	A	3
1	4		Emissions	A	5
2	3	Mode Share	Transfers	A	5
2	4		Emissions	A	5
3	4	Transfers	Emissions	A	1

A
B

AHP Analytic Hierarchy Process

n= 4 Input 9

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		23%
2	Mode Share		12%
3	Transfers		58%
4	Emissions		7%

Name	Weight	Date
Anthony Ling (C)	1	22/04/2016

α: 0,1 CR: 9% (Consistency Ratio) Scale: 1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Travel time	Mode Share	A	3
1	3		Transfers	B	4
1	4		Emissions	A	3
2	3	Mode Share	Transfers	B	5
2	4		Emissions	A	3
3	4	Transfers	Emissions	A	5

A
B

AHP Analytic Hierarchy Process

n= 4 Input 10

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		42%
2	Mode Share		13%
3	Transfers		39%
4	Emissions		6%

Name	Weight	Date
Rui Neiva (C)	1	22/04/2016

α: 0,1 CR: 8% (Consistency Ratio) Scale: 1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Travel time	Mode Share	A	5
1	3		Transfers	A	1
1	4		Emissions	A	5
2	3	Mode Share	Transfers	B	4
2	4		Emissions	A	5
3	4	Transfers	Emissions	A	5

A
B

AHP Analytic Hierarchy Process

n= 4 Input 11

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		63%
2	Mode Share		26%
3	Transfers		6%
4	Emissions		5%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Victor Pinto (P)	1	22/04/2016	0,1	15%	1

i	j	A	B	more important ? A or B	Scale (1-9)		
1	2	Travel time	Mode Share	A	5	1	A2
1	3		Transfers	A	7	3	A9
1	4		Emissions	A	9		
2	3	Mode Share	Transfers	A	5		
2	4		Emissions	A	9	2	A5
3	4	Transfers	Emissions	A	1		

Scale: A B

AHP Analytic Hierarchy Process

n= 4 Input 12

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		23%
2	Mode Share		23%
3	Transfers		14%
4	Emissions		39%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Tiago Farias (A)	1	19/07/2016	0,1	7%	1

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Travel time	Mode Share	A	1
1	3		Transfers	A	2
1	4		Emissions	B	2
2	3	Mode Share	Transfers	A	1
2	4		Emissions	A	1
3	4	Transfers	Emissions	B	4

Scale: A B

AHP Analytic Hierarchy Process

n= 4 Input 13

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		70%
2	Mode Share		19%
3	Transfers		6%
4	Emissions		5%

Name	Weight	Date	α:	CR:	Scale
Wagner C Martins (C)	1	19/07/2016	0,1	13%	1

Consistency Ratio

i	j	A	B	A or B	Scale (1-9)			
1	2	Travel time	Mode Share	A	7	1	A4	A
1	3		Transfers	A	9			B
1	4		Emissions	A	9	3	A9	
2	3	Mode Share	Transfers	A	3			
2	4		Emissions	A	7	2	A4	
3	4	Transfers	Emissions	A	1			

AHP Analytic Hierarchy Process

n= 4 Input 14

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		67%
2	Mode Share		22%
3	Transfers		6%
4	Emissions		5%

Name	Weight	Date	α:	CR:	Scale
André Remédio (C)	1	19/07/2016	0,1	20%	1

Consistency Ratio

i	j	A	B	A or B	Scale (1-9)			
1	2	Travel time	Mode Share	A	7	1	A3	A
1	3		Transfers	A	7	3	A9	B
1	4		Emissions	A	9			
2	3	Mode Share	Transfers	A	5			
2	4		Emissions	A	7	2	A4	
3	4	Transfers	Emissions	A	1			

AHP Analytic Hierarchy Process

n= 4 | Input 15

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		52%
2	Mode Share		3%
3	Transfers		8%
4	Emissions		37%

Name	Weight	Date	α:	CR	Scale
David Levinson (A)	1	19/07/2016	0,1	17%	1

Consistency Ratio

i	j	A	B	more important ? A or B	Scale (1-9)		
1	2	Travel time	Mode Share	A	9	2	A9
1	3		Transfers	A	9		
1	4		Emissions	A	2		
2	3	Mode Share	Transfers	B	9	1	B3
2	4		Emissions	B	9		
3	4	Transfers	Emissions	B	9	3	B4

A
B

AHP Analytic Hierarchy Process

n= 4 | Input 16

Objective: Transport

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		44%
2	Mode Share		11%
3	Transfers		19%
4	Emissions		26%

Name	Weight	Date	α:	CR	Scale
António Couto (A)	1	19/07/2016	0,1	2%	1

Consistency Ratio

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Travel time	Mode Share	A	4
1	3		Transfers	A	2
1	4		Emissions	A	2
2	3	Mode Share	Transfers	B	2
2	4		Emissions	B	2
3	4	Transfers	Emissions	B	2

A
B

AHP Analytic Hierarchy Process	n=	4	Input	17
Objective: Transport				

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Travel time		13%
2	Mode Share		30%
3	Transfers		51%
4	Emissions		7%

Name	Weight	Date	α:	CR:	Scale
Álvaro Seco (A)	1	19/07/2016	0,1	4%	1
				Consistency Ratio	

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Travel time	Mode Share	B	3
1	3		Transfers	B	5
1	4		Emissions	A	3
2	3	Mode Share	Transfers	B	2
2	4		Emissions	A	4
3	4	Transfers	Emissions	A	5

A
B

The answers for the subcriteria – Real Estate, Density, Mixed-use and Accessibility – are depicted below.

Consolidated answers:

AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version **07.06.2015** Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n=	4	Number of criteria (2 to 10)	Scale:	1	Linear
N=	17	Number of Participants (1 to 20)	α:	0,1	Consensus: 73,5%
p=	0	selected Participant (0=consol.)	2	7	Consolidated

Objective Land use

Author MPS

Date 18-Mar-16 Thresh: 1E-07 Iterations: 6 EVM check: 2,5E-08

Table	**Criterion**	**Comment**	**Weights**	**Rk**
	1 Real estate		18,1%	3
	2 Mixed-use		15,7%	4
	3 Density		31,3%	2
	4 Accessibility		34,9%	1

Result

Eigenvalue lambda: 4,028

Consistency Ratio 0,37 GCI: 0,04 CR: 1,0%

Matrix

		Real estate 1	Mixed-use 2	Density 3	Accessibility 4	0 5	0 6	0 7	0 8	0 9	0 10	normalized principal Eigenvector
Real estate	1	-	1	5/7	1/2	-	-	-	-	-	-	18,06%
Mixed-use	2	1	-	3/7	1/2	-	-	-	-	-	-	15,73%
Density	3	1 2/5	2 2/5	-	1	-	-	-	-	-	-	31,33%
Accessibility	4	2	2 1/6	1	-	-	-	-	-	-	-	34,88%

Individual answers:

AHP Analytic Hierarchy Process

n= 4 Input 1

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		28%
2	Mixed-use		13%
3	Density		31%
4	Accessibility		28%

Name	Weight	Date
Anson Stewart (A)	1	18/03/2016

α: 0,1 CR: 1% Consistency Ratio 1 Scale

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Real estate	Mixed-use	A	2
1	3		Density	A	1
1	4		Accessibility	A	1
2	3	Mixed-use	Density	B	3
2	4		Accessibility	B	2
3	4	Density	Accessibility	A	1

A
B

AHP Analytic Hierarchy Process

n= 4 Input 2

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		5%
2	Mixed-use		30%
3	Density		53%
4	Accessibility		12%

Name	Weight	Date
Antonio Nelson (A)	1	18/03/2016

α: 0,1 CR: 2% Consistency Ratio 1 Scale

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Real estate	Mixed-use	B	6
1	3		Density	B	8
1	4		Accessibility	B	3
2	3	Mixed-use	Density	B	2
2	4		Accessibility	A	3
3	4	Density	Accessibility	A	5

A
B

AHP Analytic Hierarchy Process

n= 4 Input 3

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		28%
2	Mixed-use		5%
3	Density		12%
4	Accessibility		55%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Sebastian Ebert (A)	1	18/03/2016	0,1	20%	1

i	j	Criteria A	Criteria B	more important? A or B	Scale (1-9)		
1	2	Real estate	Mixed-use	A	5		
1	3		Density	A	5	2	A2
1	4		Accessibility	B	4		
2	3	Mixed-use	Density	B	5	1	B2
2	4		Accessibility	B	5	2	B9
3	4	Density	Accessibility	B	5		

AHP Analytic Hierarchy Process

n= 4 Input 4

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		47%
2	Mixed-use		4%
3	Density		18%
4	Accessibility		30%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
António Lobo (A)	1	18/03/2016	0,1	11%	1

i	j	Criteria A	Criteria B	more important? A or B	Scale (1-9)		
1	2	Real estate	Mixed-use	A	9		
1	3		Density	A	5	1	A3
1	4		Accessibility	A	1	3	A2
2	3	Mixed-use	Density	B	5		
2	4		Accessibility	B	7		
3	4	Density	Accessibility	A	1	2	B2

AHP Analytic Hierarchy Process

n= 4 Input 5

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		10%
2	Mixed-use		30%
3	Density		30%
4	Accessibility		30%

Name	Weight	Date	α:	CR:	Scale
Jorge Freire Sousa (A)	1	22/04/2016	0,1	0%	1

Consistency Ratio

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Real estate	Mixed-use	B	3
1	3		Density	B	3
1	4		Accessibility	B	3
2	3	Mixed-use	Density	A	1
2	4		Accessibility	A	1
3	4	Density	Accessibility	A	1

A

B

AHP Analytic Hierarchy Process

n= 4 Input 6

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		13%
2	Mixed-use		35%
3	Density		16%
4	Accessibility		35%

Name	Weight	Date	α:	CR:	Scale
Lino Marujo (A)	1	22/04/2016	0,1	1%	1

Consistency Ratio

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Real estate	Mixed-use	B	3
1	3		Density	A	1
1	4		Accessibility	B	3
2	3	Mixed-use	Density	A	2
2	4		Accessibility	A	1
3	4	Density	Accessibility	B	2

A

B

AHP Analytic Hierarchy Process

n= 4 Input 7

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		21%
2	Mixed-use		30%
3	Density		25%
4	Accessibility		25%

Name	Weight	Date	α:	Consistency Ratio	Scale
Todd Litman (A)	1	22/04/2016	0,1	CR: 2%	1

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Real estate	Mixed-use	B	2
1	3		Density	A	1
1	4		Accessibility	A	1
2	3	Mixed-use	Density	A	1
2	4		Accessibility	A	1
3	4	Density	Accessibility	A	1

A

B

AHP Analytic Hierarchy Process

n= 4 Input 8

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		66%
2	Mixed-use		4%
3	Density		8%
4	Accessibility		22%

Name	Weight	Date	α:	Consistency Ratio	Scale
Bert van Wee (A)	1	22/04/2016	0,1	CR: 14%	1

i	j	A	B	more important ? A or B	Scale (1-9)		
1	2	Real estate	Mixed-use	A	9	2	A9
1	3		Density	A	9		
1	4		Accessibility	A	5		
2	3	Mixed-use	Density	B	5	1	B2
2	4		Accessibility	B	5		
3	4	Density	Accessibility	B	5	2	B3

A

B

AHP Analytic Hierarchy Process

n= 4 Input 9

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		25%
2	Mixed-use		25%
3	Density		25%
4	Accessibility		25%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Anthony Ling (C)	1	22/04/2016	0,1	0%	1

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Real estate	Mixed-use	A	1
1	3		Density	A	1
1	4		Accessibility	A	1
2	3	Mixed-use	Density	A	1
2	4		Accessibility	A	1
3	4	Density	Accessibility	A	1

A

B

AHP Analytic Hierarchy Process

n= 4 Input 10

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		25%
2	Mixed-use		25%
3	Density		25%
4	Accessibility		25%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Rui Neiva (C)	1	22/04/2016	0,1	0%	1

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Real estate	Mixed-use	A	1
1	3		Density	A	1
1	4		Accessibility	A	1
2	3	Mixed-use	Density	A	1
2	4		Accessibility	A	1
3	4	Density	Accessibility	A	1

A

B

AHP Analytic Hierarchy Process

n= 4 | Input 11

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		8%
2	Mixed-use		4%
3	Density		67%
4	Accessibility		21%

Name	Weight	Date	α:	Consistency Ratio	Scale
Victor Pinto (P)	1	22/04/2016	0,1	CR: 20%	1

i	j	A	B	more important ? A or B	Scale (1-9)			Scale
1	2	Real estate	Mixed-use	A	3			A
1	3		Density	B	7			B
1	4		Accessibility	B	6	2	B3	
2	3	Mixed-use	Density	B	9	3	B9	
2	4		Accessibility	B	5			
3	4	Density	Accessibility	A	7	1	A3	

AHP Analytic Hierarchy Process

n= 4 | Input 12

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		7%
2	Mixed-use		32%
3	Density		30%
4	Accessibility		30%

Name	Weight	Date	α:	Consistency Ratio	Scale
Tiago Farias (P)	1	19/07/2016	0,1	CR: 0%	1

i	j	A	B	more important ? A or B	Scale (1-9)	Scale
1	2	Real estate	Mixed-use	B	5	A
1	3		Density	B	4	B
1	4		Accessibility	B	4	
2	3	Mixed-use	Density	A	1	
2	4		Accessibility	A	1	
3	4	Density	Accessibility	A	1	

AHP Analytic Hierarchy Process

n= 4 Input 13

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		6%
2	Mixed-use		15%
3	Density		38%
4	Accessibility		41%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
Wagner C Martins (C)	1	19/07/2016	0,1	1%	1

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Real estate	Mixed-use	B	3
1	3		Density	B	5
1	4		Accessibility	B	7
2	3	Mixed-use	Density	B	3
2	4		Accessibility	B	3
3	4	Density	Accessibility	A	1

A
B

AHP Analytic Hierarchy Process

n= 4 Input 14

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		5%
2	Mixed-use		10%
3	Density		54%
4	Accessibility		31%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
André Remédio (C)	1	19/07/2016	0,1	9%	1

i	j	A	B	more important ? A or B	Scale (1-9)
1	2	Real estate	Mixed-use	B	3
1	3		Density	B	7
1	4		Accessibility	B	7
2	3	Mixed-use	Density	B	5
2	4		Accessibility	B	5
3	4	Density	Accessibility	A	3

A
B

AHP Analytic Hierarchy Process

n= 4 Input 15

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		52%
2	Mixed-use		3%
3	Density		8%
4	Accessibility		37%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
David Levinson (A)	1	19/07/2016	0,1	17%	1

i	j	Criteria A	B	more important ? A or B	Scale (1-9)		
1	2	Real estate	Mixed-use	A	9	2	A9
1	3		Density	A	9		
1	4		Accessibility	A	2		
2	3	Mixed-use	Density	B	9	1	B3
2	4		Accessibility	B	9		
3	4	Density	Accessibility	B	9	3	B4

AHP Analytic Hierarchy Process

n= 4 Input 16

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		8%
2	Mixed-use		20%
3	Density		37%
4	Accessibility		35%

Name	Weight	Date	α:	CR: Consistency Ratio	Scale
António Couto (A)	1	19/07/2016	0,1	0%	1

i	j	Criteria A	B	more important ? A or B	Scale (1-9)
1	2	Real estate	Mixed-use	B	3
1	3		Density	B	5
1	4		Accessibility	B	4
2	3	Mixed-use	Density	B	2
2	4		Accessibility	B	2
3	4	Density	Accessibility	A	1

AHP Analytic Hierarchy Process n= 4 Input 17

Objective: Land use

Only input data in the light green fields!

Please compare the importance of the elements in relation to the objective and fill in the table: Which element of each pair is more important, **A or B**, and **how much** more on a scale 1-9 as given below.

Once completed, you might adjust highlighted comparisons 1 to 3 to improve consistency.

n	Criteria	Comment	RGMM
1	Real estate		8%
2	Mixed-use		14%
3	Density		39%
4	Accessibility		39%

Name	Weight	Date	α:	Consistency Ratio CR:	Scale
Álvaro Seco (A)	1	19/07/2016	0,1	0%	1

i	j	Criteria A	Criteria B	more important ? A or B	Scale (1-9)
1	2	Real estate	Mixed-use	B	2
1	3		Density	B	5
1	4		Accessibility	B	5
2	3	Mixed-use	Density	B	3
2	4		Accessibility	B	3
3	4	Density	Accessibility	A	1

A

B

A.10. AM Home based work O/D matrices by mode

Matrices for the No Build investment alternative from chapter 5.

Name	MC_HBW				
Description	AM Home based work O/D matrices by mode				
Unit	Trips				
Use	Accessibility, mode share, travel time calculations				
Investment Alternative	No Build				
Year	2030				
Zones	986				
Mode	WALK	WAT	DAT	SOV	APAX
Total trips	301,629	263,075	125,015	2,426,192	86,982
O/D pair with more trips	224-224	70-20	220-24	890-882	224-225
Value (trips)	2,495	277	56	864	51
Origin producing more trips	224	70	220	984	985
Value (trips)	3,874	4756	873	13,642	654
Destination attracting more trips	224	33	33	260	94
Value (trips)	3,370	7,175	4,984	11,963	1,625
Matrices Folder	No Build				
TAZs locations file	TAZ				

Matrices for the BRT investment alternative from chapter 5.

Name	MC_HBW				
Description	AM Home based work O/D matrices by mode				
Unit	Trips				
Use	Accessibility, mode share, travel time calculations				
Investment Alternative	BRT				
Year	2030				
Zones	986				
Mode	WALK	WAT	DAT	SOV	APAX
Total trips	300,846	264,278	124,941	2,425,634	86,925
O/D pair with more trips	224-224	70-20	220-24	890-882	224-225
Value (trips)	2,495	277	56	864	51
Origin producing more trips	224	70	220	984	985
Value (trips)	3,874	4,756	873	13,642	654
Destination attracting more trips	224	33	33	260	94
Value (trips)	3,370	7,175	4,984	11,963	1,625
Matrices Folder	BRT				
TAZs locations file	TAZ				

Matrices for the LRT investment alternative from chapter 5.

Name	MC_HBW				
Description	AM Home based work O/D matrices by mode				
Unit	Trips				
Use	Accessibility, mode share, travel time calculations				
Investment Alternative	LRT				
Year	2030				
Zones	986				
Mode	WALK	WAT	DAT	SOV	APAX
Total trips	272,595	258,945	131,939	2,274,198	78,920
O/D pair with more trips	224-224	70-20	224-24	890-882	200-201
Value (trips)	2,228	255	49	741	49
Origin producing more trips	224	70	220	984	985
Value (trips)	3,874	4,756	873	13,642	654
Destination attracting more trips	225	33	33	260	94
Value (trips)	3,370	7,175	4,984	11,963	1,625
Matrices Folder	LRT				
TAZs locations file	TAZ				

A.11. AM transit travel time skims

Travel time matrices skims used for accessibility and travel time calculations from chapter 5. Link for the file: Skims.

A.12. Transfer data

Total (24-hour) number of transfers, used for transfers calculations from chapter 5. Link for the file: Transfers.

A.13. Ridership data

Total (24-hour) Transit ridership, used for revenues calculations from chapter 5. Link for the files: Ridership.

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